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VACUUM IGNITION CHARACTERISTICS OF FLOX/DIBORANE AND OXYGEN DIFLUORIDE/DIBORANE

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Reaction Motors Division

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FOREWORD

This is the interim final report covering work performed by Thiokol Chemical Corporation, Reaction Motors Division, Denville, New Jersey, under National Aeronautics and Space Administration Contract NAS 7-660. The internal report number is Report RMD 5534-FI (Interim).

The technical manager of the program is Mr. Robert W. Rowley, Liquid Propulsion Section, Jet Propulsion Laboratory, Pasadena, California. The NASA Project Manager is Dr. Robert S. Levine, OART, NASA Headquarters, Washington, D. C.

The technical program described herein was conducted during the period 15 February 1968 through 15 October 1968. The project leader is Mr. Thomas F. Seamans. The principal investigator is Mr. George R. Mistler.

ABSTRACT

The vacuum ignition characteristics of Flox/diborane and OF_2/diborane have been investigated in 100 lbf thrust rocket engines to determine potential problem areas and define design concepts required to insure reliable vacuum starting of space engines. Parameters investigated were: oxidizer (Flox and OF_2), hardware temperature (70°, 0°, -100° and -200°F), propellant temperature (Flox at -320°F, OF_2 at -320° and -160°F, diborane at -100° and -10°F), propellant lead/lag, design chamber pressure (20 and 100 psia) and injector configuration/dribble volume (9 pair doublet and 1 pair doublet). One strong ignition pressure spike occurred during the 46 bipropellant tests. In a singly flowed OF_2 test, a chamber pressure spike also occurred indicating reaction with condensed phase combustion residue from prior runs. Pressure fluctuations in the oxidizer manifold were common and are apparently caused by both fuel and combustion residue contaminating the oxidizer manifold. Shortest ignition delay times were obtained with Flox rather than OF_2, with the single element injector, the 100 psia chamber and no propellant lead. Unexpectedly, neither hardware temperature nor propellant temperature affected ignition delay times. The dominant ignition reactions of these propellants appear to be gas phase reactions in the engines. From the standpoints of ignition behavior and system stability during start-up, an engine for OF_2/B_2H_6 multiple-pulse operation in space requires a high design chamber pressure and a minimum dribble volume, multiple element injector which has small diameter, long l/D orifices. The system should provide for simultaneous propellant injection, cold diborane, cold hardware and an oxidizer-rich tail-off.

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I. INTRODUCTION

The high energy propellant combination, oxygen difluoride/diborane, offers the attractive characteristics of excellent performance, high density and hypergolic ignition necessary to improve the mission capability of future spacecraft. These characteristics are especially desirable for high response, low thrust attitude control engines.

Mission studies have shown that the oxygen difluoride/diborane propellant combination provides a payload capability comparable to any of the fluorine oxidized bipropellant systems currently under consideration and superior to that of the oxygen/hydrogen system. For space propulsion systems requiring very high velocity increments per stage, the payload capability of OF_2/B_2H_6 exceeds that of F_2/H_2 and is matched only by F_2/B_2H_6. Further comparison with fluorine shows that OF_2 has a decided advantage in the areas of handling and space storability where weight penalties incurred by tank insulation are reduced. Oxygen difluoride, however, is expensive. The less expensive 70 percent F_2/30 percent O_2 Flox mixture, whose overall composition closely matches that of OF_2, has gained acceptance as a suitable substitute for pre-flight hardware testing and evaluation.

A major problem of contemporary attitude control engines operating with earth storable propellants, such as nitrogen tetroxide and hydrazine type fuels, is the lack of repeatability and reliability of ignition of these hypergols. These high response engine systems are characterized by ignition pressure spikes which occur at space conditions and which sometimes cause hardware failures. Another phenomenon experienced with these space engines is severe pressure perturbations in the oxidizer manifold which have caused propellant valve failures and, in extreme cases, loss of the injector face. It was not known if these starting transient problems were unique to earth storable propellant combinations or if they would also occur when high energy space storable propellant combinations were used.

The purpose of this eight month technical program is to define vacuum starting characteristics and potential problem areas in vacuum ignition of space engines using Flox/diborane and OF_2/diborane as propellants.

The program consists of two technical tasks as follows:

TASK I - VACUUM IGNITION OF FLOX/DIBORANE

The primary effort of the program and of this task was an experimental investigation of the vacuum ignition characteristics of a 100 lb thrust rocket engine using the Flox/diborane propellant combination. The engine and operating parameters investigated were design chamber pressure, dribble volume/injector configuration, propellant lead/lag, oxidizer temperature, fuel temperature and injector/thrust chamber temperature. A correlative effort to define the physical and chemical mechanisms which control starting under the test conditions and to define design concepts and operational procedures required to insure reliable vacuum starting of Flox/diborane space engines was also undertaken.

TASK II - INTERCHANGEABILITY OF FLOX AND OF_2

This task consists of experimental and analytical studies to determine the effects on engine ignition characteristics when OF_2 is substituted for the Flox. Selected Task I tests were repeated but using OF_2 as the oxidizer. Also, tests were conducted with the OF_2 at -150^0F to investigate the effects of the allowable higher liquid temperature of this oxidizer. From the tests and supporting analyses, changes in design concepts and hardware required for reliable vacuum starting of space engines when OF_2 is substituted for Flox were determined.

The results of the program are discussed in subsequent sections.

II. SUMMARY

The purpose of the program reported herein is to define vacuum starting characteristics and potential problem areas in vacuum ignition of space engines using Flox/diborane and OF_2/diborane as propellants.

This report is the final report of an eight-month program which consisted of two technical tasks as follows. The primary effort of the program and of Task I was an experimental investigation of the vacuum ignition characteristics of a 100 lb thrust rocket engine using the Flox/diborane propellant combination. The engine and operating parameters investigated were design chamber pressure, dribble volume/injector configuration, propellant lead/lag, oxidizer temperature, fuel temperature and injector/thrust chamber temperature. A correlative effort to define the physical and chemical mechanisms which control starting under the test conditions and to define design concepts and operational procedures required to insure reliable vacuum starting of Flox/diborane space engines was also undertaken.

Task II consisted of experimental and analytical studies to determine the effects on engine ignition characteristics when OF_2 is substituted for the Flox. Selected Task I tests were repeated but using OF_2 as the oxidizer. Also the effects of the allowable higher liquid temperature of this oxidizer were investigated.

Ignition tests were conducted with 100-lb thrust engines at simulated altitudes in excess of 250,000 ft. The test hardware consists of two impinging stream injectors which mate interchangeably with two thrust chambers that differ primarily in design chamber pressure: 100 psia and 20 psia. Both chambers have a contraction ratio of 6.25 and an L* of 25 inches.

Two injectors were used to evaluate effects of dribble volume. One injector is a nine element doublet injector representative of flight-type hardware. The other is a single element doublet with about one-third the internal volume of the nine pair injector.

The propellant valves are straight through, solenoid operated, poppet type valves incorporating stellite seats and seals. Short stand-off tubes with drilled inserts were used between the propellant valves and injectors

to permit conditioning the injector to one temperature and each propellant and its valve to another.

Primary instrumentation was high response, flush mounted piezoelectric pressure transducers in the thrust chambers and each injector manifold. Frequency response was well in excess of 25 kHz.

A total of 48 vacuum ignition tests was conducted: 30 with Flox/diborane, 16 with OF_2/diborane and one each with singly flowed OF_2 and diborane. For the various tests, the engine hardware was conditioned to 70°, 0°, -100° and -200°F. Propellant and valve conditioning was as follows: Flox at -320°F, OF_2 at -320° and -160°F, and diborane at -100° and -10°F. Propellant injection included fuel lead, simultaneous and oxidizer lead with the two injectors and chambers. Tests included those with clean injectors as well as pre-fired injectors. The test hardware and system were in excellent condition at the conclusion of the test program. There was no evidence of any burning, pitting, erosion or pressure stresses.

One strong chamber ignition pressure spike occurred during the program. It occurred with cold OF_2/B_2H_6, oxidizer lead, the 100 psia chamber and the nine pair injector conditioned to -100°F. A chamber pressure spike also occurred when OF_2 was flowed singly at otherwise identical conditions. The singly flowed OF_2 apparently reacted with condensed phase combustion residue which was dispersed over all interior surfaces. Analysis showed that the deposits were mainly amorphous elemental boron which can result from fuel-rich combustion during tail-off of prior pulses. It is suspected that the OF_2/B_2H_6 ignition pressure spike was due to reaction of OF_2 with the combustion residue.

Generally, ignition pressure transients in the thrust chamber were smooth with little overshoot. However, pressure fluctuations in the oxidizer manifold were common and sometimes affected the ignition delay times markedly. Random pressure peaks in the oxidizer manifold result apparently from contamination of the manifold by both fuel and the condensed phase combustion residue. The fuel enters prior to oxidizer flow particularly in runs with a programmed fuel lead. The combustion residue enters during tail-off of the preceding pulse. Oxidizer manifold pressure peaking was greater with Flox rather than OF_2, with a fuel lead, with the single element injector and with a pre-fired injector.

High frequency pressure oscillations also occurred in the oxidizer manifold but only with OF_2 and hardware temperatures of 0° and $+70^\circ F$. These oscillations appear to be related to an acoustic phenomenon which is excited by injector geometry and heat transfer to the oxidizer. The oscillations can be avoided by lower injector temperatures.

The shortest ignition delay times were obtained with Flox/diborane, the single element injector, the 100 psia chamber and no propellant lead. Conversely, ignition delay times were longer with OF_2 as oxidizer, the 20 psia chamber, the nine element doublet injector and with both fuel and oxidizer leads. Ignition delay times were also extended when high pressure peaks in the oxidizer manifold momentarily interrupted the propellant flow. Unexpectedly, neither hardware temperature nor propellant temperature affected ignition delay times in the engines. It is deduced from the data that the dominant ignition reactions of these propellants are gas phase reactions.

The results of the program yield design concepts and operating procedures which must be considered preliminary until verified by further study beyond that performed in this eight-month study. In summary, from the standpoints of ignition behavior and system stability during start-up, an engine for OF_2/B_2H_6 multiple-pulse operation in space should be designed with a high chamber pressure and a minimum dribble volume, multiple element injector having small diameter, long l/D orifices. The system should provide for simultaneous propellant injection or a slight oxidizer lead, cold diborane, cold hardware and an oxidizer-rich tail-off. Other usual features of high response engines such as fast-acting valves and flow control by system ΔP are of course necessary.

Further work is required to extend the investigation to parameters and ranges outside those covered to date and to further identify the combustion residue, its role in manifold and chamber spiking, and its spatial and temporal origins in the engines. Added specialized instrumentation is needed to further elucidate starting mechanisms and additional system aspects (other valve-types, ullage volume, temperatures, etc.) require investigation.

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III. EXPERIMENTAL SYSTEM

The experimental system was designed to provide the test data required to meet the program objectives. It consisted of test hardware, test system and instrumentation system. These are discussed in the following paragraphs.

A. TEST HARDWARE

1. Thrust Chambers

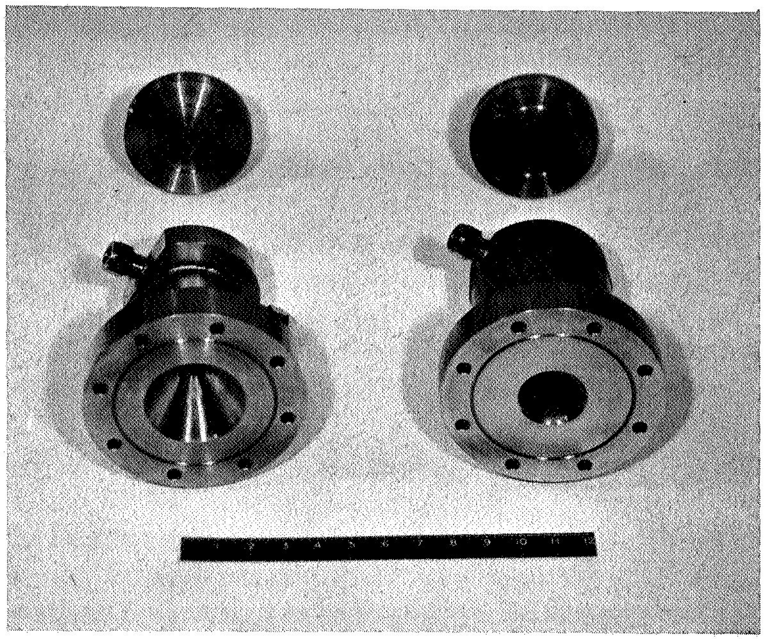
Chambers and nozzles were designed for a thrust of 100 lbs under space conditions. At 100 psia chamber pressure, a Flox/B_2H_6 mixture ratio of 3 and an exit area ratio of 25, the vacuum specific impulse is approximately 410 sec. The engines were designed for a specific impulse of 400 which corresponds to a total flowrate of 0.25 lb/sec at an O/F of 3. To evaluate the expected effect of design chamber pressure on ignition, two nozzle-chamber combinations were used: one designed for 100 psia and the second for 20 psia chamber pressure. Each has a contraction ratio of approximately 6.25 and an L* of approximately 25 inches. The nozzles have a 90 degree convergent angle. Throat diameters are approximately 0.8 and 1.75 in., respectively. The rounded throat contours are followed by only short expansion sections since thrust measurements and specific impulse were not required. The nozzle flange contains bolt holes and an o-ring groove to seal to the vacuum system. The upper chamber flange was designed to mount two Kistler pressure transducers and to bolt to the injector. Fig. 1 shows an exploded view of the chamber/injector assemblies.

2. Injectors

To define potential problem areas relative to dribble volume and flow paths, two injectors were used; they are interchangeable with the two chambers. Both injectors are doublets. One injector is a single element doublet to reduce injector dribble volume to a minimum. The second injector is also a doublet but it contains nine pairs of orifices and a larger distribution manifold more representative of flight hardware. Rupe's criteria of unity momentum ratio (Ref. 1) was used for injector design. At design flows, injection velocities are 48 ft/sec and 112 ft/sec for

9 Pair Doublet Injector

100 lbf Thrust Chamber, 100 psia



Single Element Doublet Injector

100 lbf Thrust Chamber, 20 psia

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FIGURE 1. Thrust Chamber/Injector Assemblies (Exploded View)

the Flox and diborane, respectively. Steady state design flow rate is 0.1875 lb/sec for the oxidizer and 0.0625 lb/sec for the fuel. Flow control is managed by propellant tank set pressures and steady state system pressure drops. Therefore, higher than design flowrates occur during the start transient. For the nominal condition of Flox at -320^{0}F, the nine pair injector, the 100 psia chamber, the calculated peak Flox flow is 0.283 lb/sec during the start transient which is 150 percent of the steady state design flow.

A comparison of the data from the two injectors at the same design flowrates and temperature conditions indicates the extent to which flashing of the propellants within the injector must be considered in designing flight hardware.

Dribble volume is defined here as the propellant volume between the downstream side of the closed propellant valve and the downstream face of the injector. Although it is desirable to keep this volume as small as possible in flight hardware, some compromise was necessary in the test configuration. To assure thermal conditioning of the initially entering propellant to the desired propellant temperature, it was necessary to condition the propellant valve as well as the propellant. Therefore, short stand-off tubes with drilled inserts to minimize internal volumes were used between the propellant valves and the injectors. The inserts are visible in Fig. 5. Insert diameters are the same as the distribution manifolds in the nine pair injector. Liquid propellant velocities in the inserts are 20 ft/sec at design flows. The dribble volumes for the injector assemblies are given in Table I.

TABLE I

DRIBBLE VOLUMES

System	Injector 1-Pair	Injector 9-Pair
Ox Prop to Injector	.055 in.^{3}	.055 in.^{3}
Oxidizer Injector	.026 in.^{3}	.083 in.^{3}
Oxidizer Dribble Volume	.081 in.^{3}	.138 in.^{3}
Fuel Prop to Injector	.0643 in.^{3}	.0643 in.^{3}
Fuel Injector	.0305 in.^{3}	.0898 in.^{3}
Fuel Dribble Volume	.0948 in.^{3}	.1541 in.^{3}

The injectors were water flow checked to permit accurate calculations of tank pressure settings to produce design flow at steady state conditions. The water flow calibration curves are given in Figs. 2 and 3. Figs. 4 and 5 show the completed injector assemblies.

The hydraulic "flip" labelled in Figs. 2 and 3 is a phenomenon often encountered during water flow calibration of rocket engine injector orifices (Refs. 2-4). It occurs with orifices which do not have perfectly rounded entrance ports and/or sufficiently long orifice length to diameter ratios and which are flowed without a sufficiently high gas back pressure (Ref. 5). The effect is not noted during normal steady state operation where high back pressures (i.e. chamber pressure) and relatively low injection velocities prevail.

3. Propellant Valves

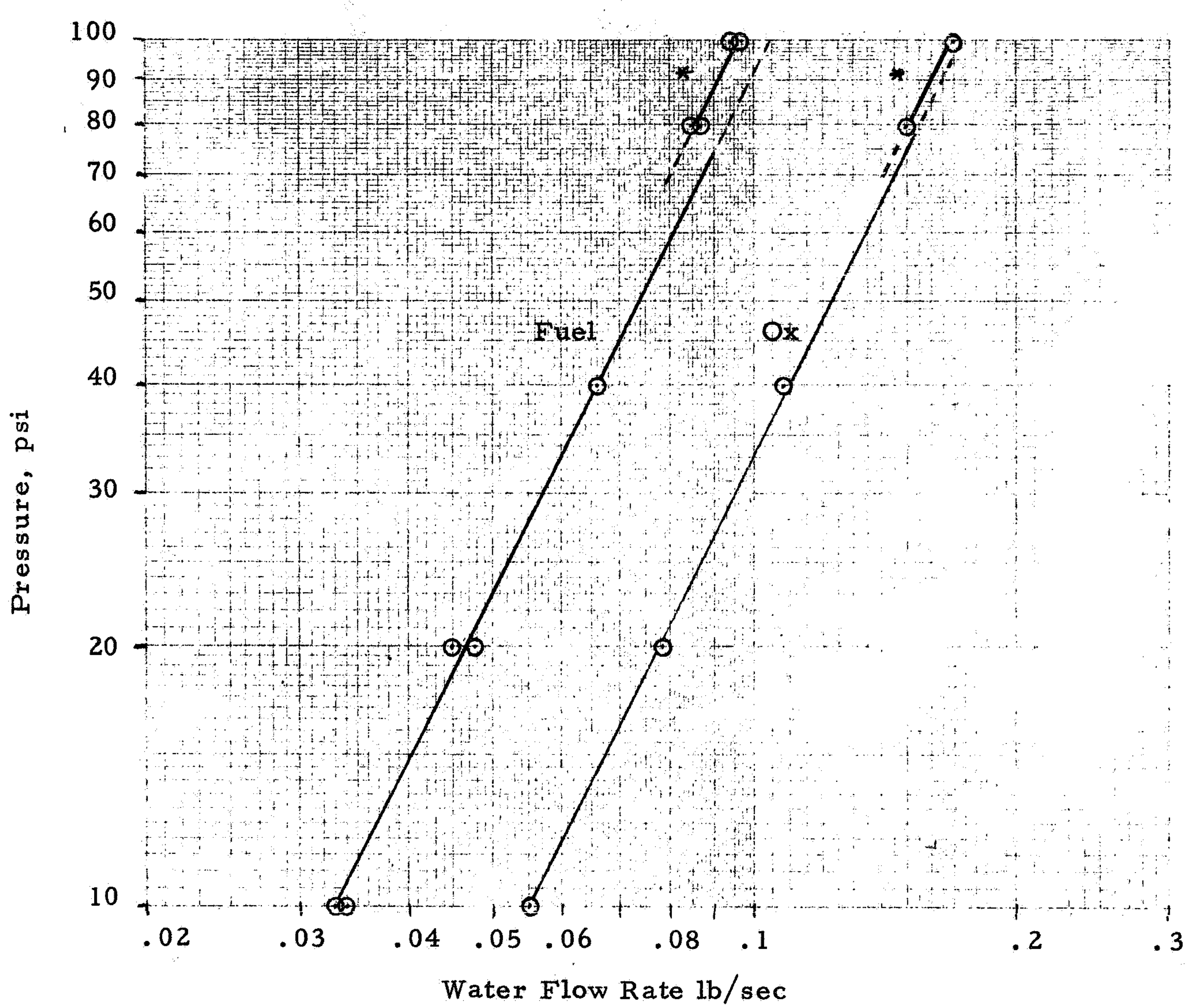
Specially designed high response pneumatically driven valves manufactured by Control Components Inc. were originally planned to be used on the program but last minute vendor technical difficulties necessitated a substitution to on-the-shelf liquid fluorine valves. Two identical units, Valcor Engineering Corporation P/N V27200-214, were used. These 1/4 inch valves are straight through solenoid operated, poppet type valves incorporating stellite seats and seals. They have low pressure drops, are designed for corrosive fluids and for immersion in liquid nitrogen. The poppets start to transfer approximately 11 msec after application of 24 VDC and are fully open by about 16 msec (but see Sec. IV. C).

4. Vacuum Ignition Test Module

Most of the components of the fuel and oxidizer pressurizing systems, Flox mixing system, the run tanks, propellant valves, and conditioning baths for the diborane safety valve and propellant tanks and valves are mounted on a three foot square by one-half inch thick aluminum plate. This assembly is called the Vacuum Ignition Test Module. Figure 6A shows a top view of the module in the process of being assembled. Figure 6B shows a front view of the module with the diborane conditioning bath removed to expose the diborane propellant tank and valve.

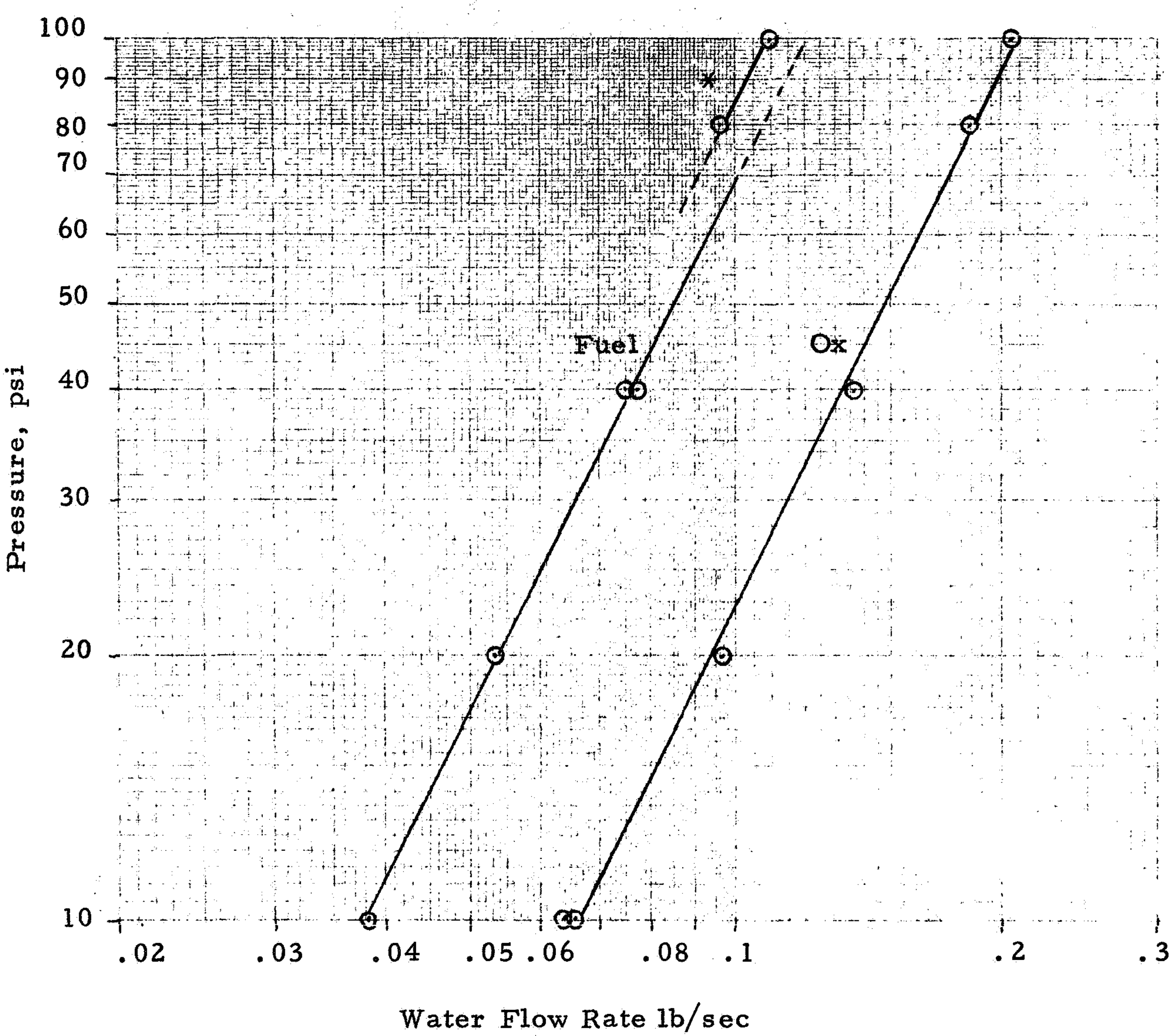
5. Vacuum/Scrubber System

The vacuum system was designed to provide an initial pressure altitude in excess of 250,000 ft. It has sufficient volume to



*Hydraulic Flip

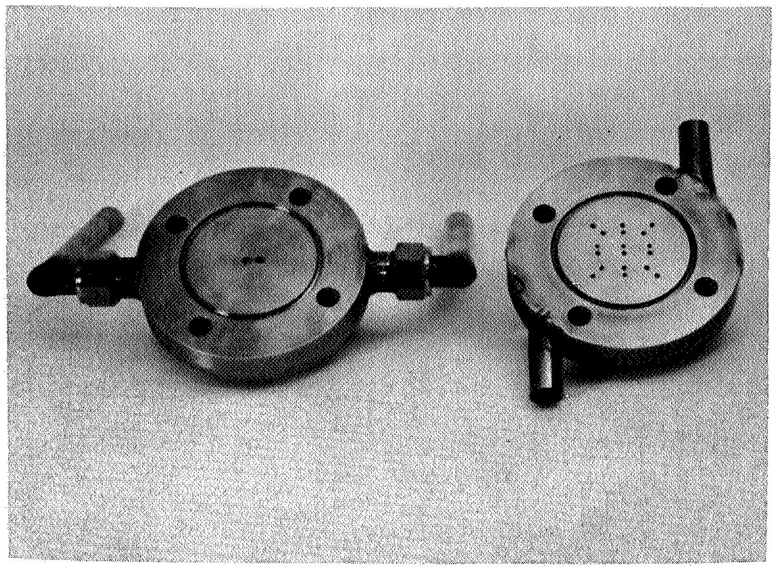
Figure 2. Water Flow Check - Valve and 9 Pair Doublet Injector (Drilled Inserts Installed)



*Hydraulic Flip

Figure 3. Water Flow Check - Valve and 1 Pair Doublet Injector (Drilled Inserts Installed)

Nine
Pair
Doublet



Single
Element
Doublet

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Figure 4

Face View of Completed Injector Assemblies

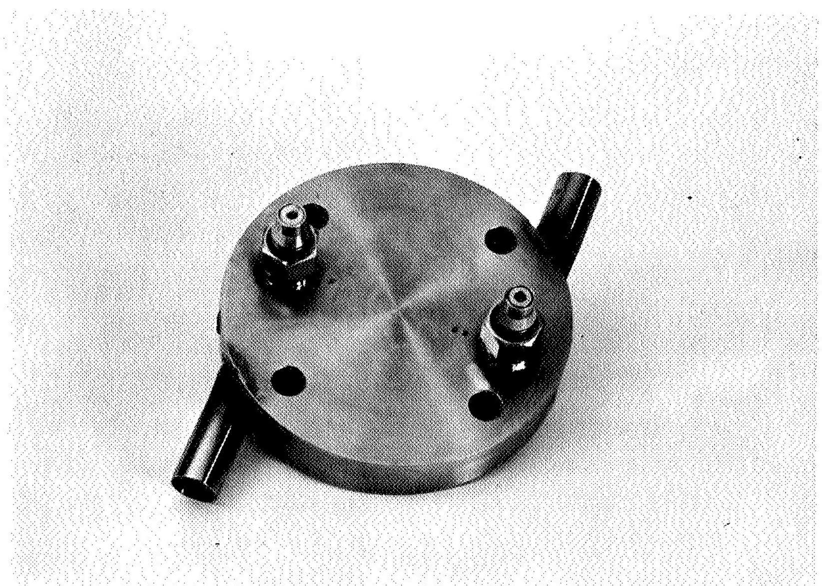

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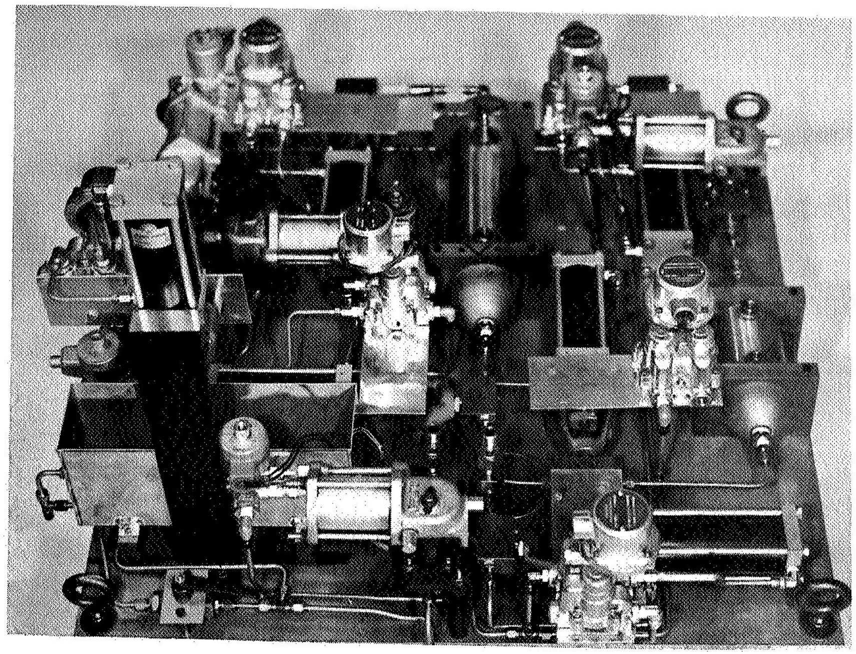
Figure 5

Back View of a Completed Injector Assembly



6A. Top View

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6B. Front View

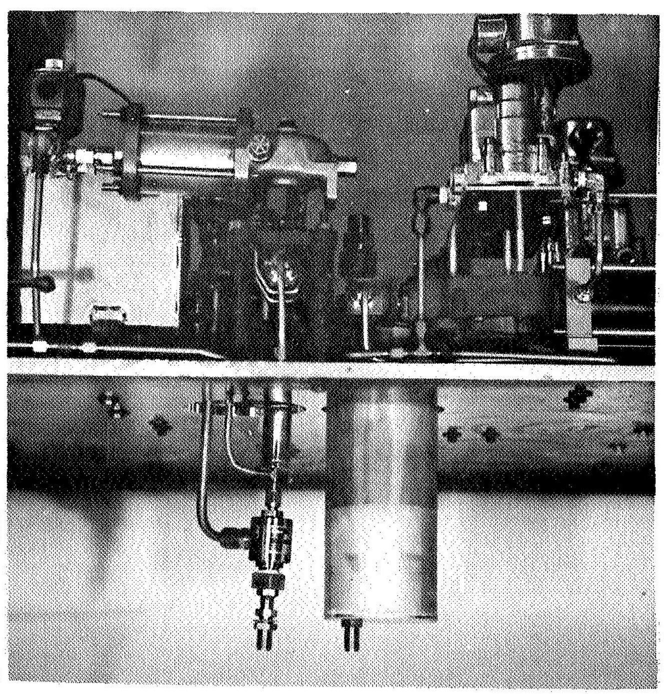

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FIGURE 6. Vacuum Ignition Test Module (In Process of Assembly)

contain the products of combustion of the 0.2 second run plus 1.8 seconds of helium purge at a pressure less than 6 psia. Calculations show that flow is choked in the nozzle throughout the ignition delay period and for the duration of the test run. The thrust chamber bath attaches to a 12 inch length of 8 inch diameter stainless steel pipe which is welded to a 5 foot length of 18 inch diameter carbon steel pipe. A 6 inch Kinney diffusion pump Model KDP-6 is backed by a Kinney mechanical pump KC-15. The pumps are isolated from the vacuum chamber during a run by a 4 inch vacuum valve to minimize ingestion of propellant and combustion products. The ultimate vacuum attained during test conditions was 2 microns which corresponds to a pressure altitude of 282,000 feet. Figure 7 shows the relation between pressure in microns and geopotential altitude in feet.

Following each altitude ignition test run the vacuum chamber was alternately pressurized to 15 psia with nitrogen and pumped to about 7 psia by a water ejector system. Approximately 97 percent of the gaseous exhaust products were removed from the vacuum chamber in this manner. The gases were entrained in the ejector stream and discharged into a treated water supply.

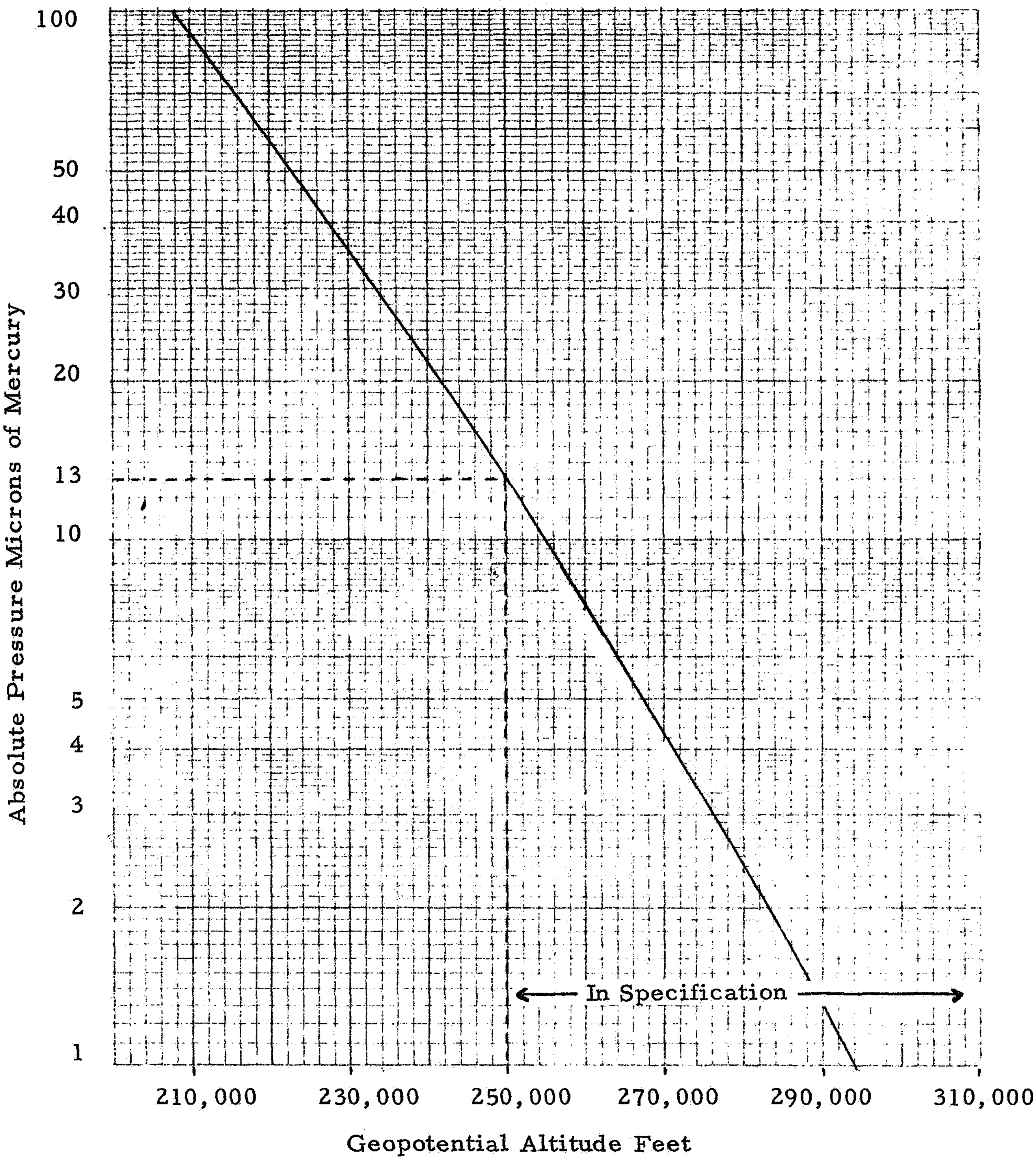
B. EXPERIMENTAL SYSTEM

The schematic of the system used for the vacuum ignition test program is given in Fig. 8. The system consists of several subsystems, diborane system, oxygen and fluorine system, helium pressurizing systems, temperature conditioning systems and a vacuum/scrubber system. Each component was meticulously cleaned and degreased prior to assembly. The techniques varied to suit the individual components and included vapor degreasing, acid baths, solvent flushing, hot detergent water flushing, rinsing and vacuum drying. Welded or brazed joints were used wherever possible and Voi-Shan conical flared fitting seals were used with AN flared fitting connectors. Following assembly with cleaned lines and fittings, the system was leak checked with helium and the oxidizer system was passivated with fluorine gas.

The experimental system is described in greater detail in the following paragraphs.

1. Diborane System

This system provides the proper amount of diborane in the fuel propellant tank for approximately 200 msec of steady state operation. It consists of (1) a diborane storage tank with suitable gas side and liquid



NOTE: Data converted from NASA U.S. Standard Atmosphere, 1962 Table IV.

Figure 7. Pressure Vs Altitude

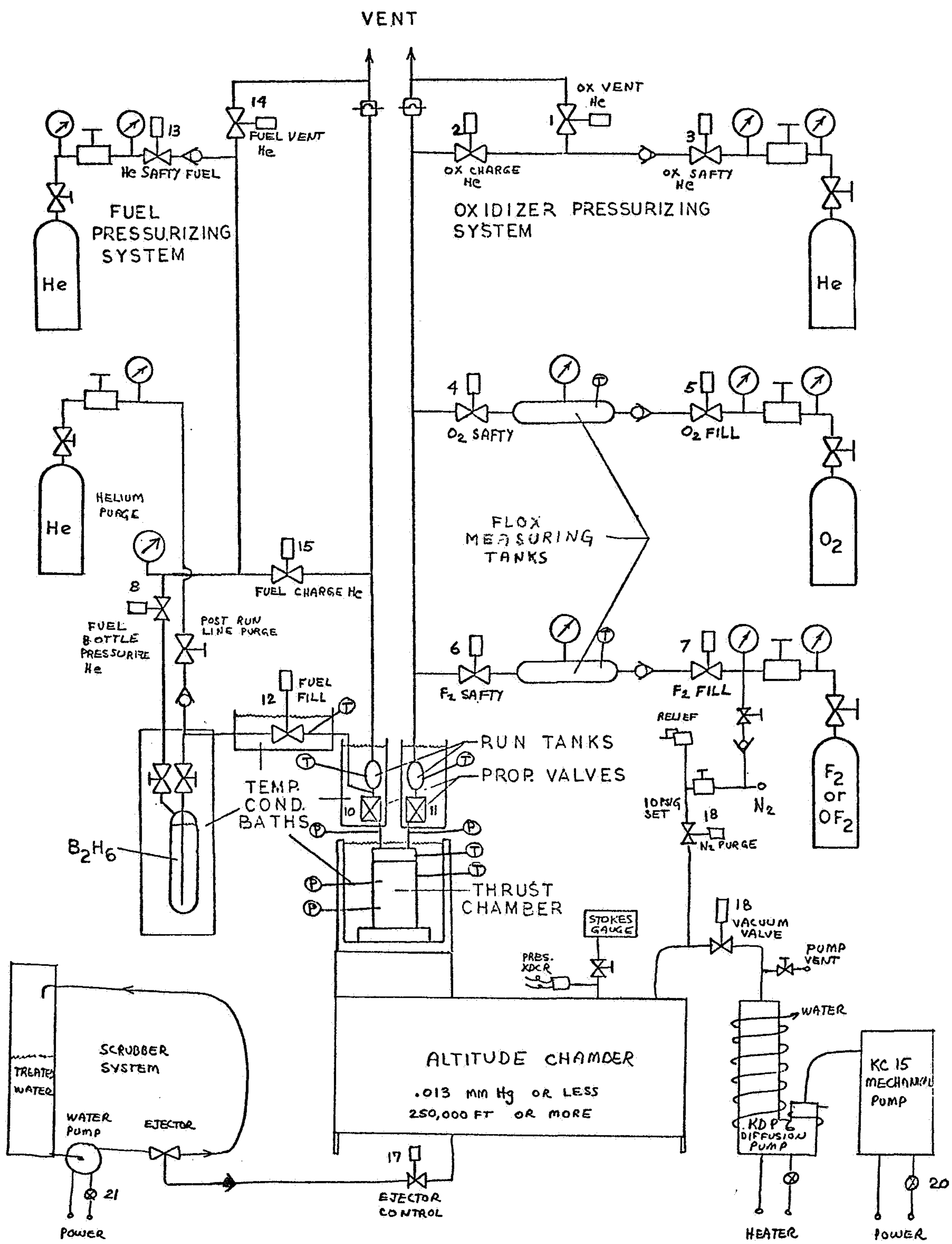


Figure 8

Vacuum Ignition Test System for Flox/B_2H_6 and OF_2/B_2H_6

side hand valves to permit transfer of the diborane into the test run tank, (2) a remotely operated cryogenic fuel fill valve and (3) a run tank and solenoid operated propellant valve. Each subsystem is maintained at -100°F with crushed dry ice in separate conditioning baths. Prior to filling the run tank, the system is evacuated from the altitude chamber to the closed liquid transfer hand valve located on the diborane storage tank. This provides vacuum fill of the diborane up to the propellant valve seat thus eliminating trapped gases which could influence start transients. Following each run, the run tank, propellant valve and injector are purged with helium. The fill line, fill valve and run tank are purged with helium through the fuel charge and vent valves to atmosphere.

2. Fluorine and Oxygen System

This system is used to make the 70/30 Flox mixture from gaseous fluorine and oxygen. It consists of regulated sources of oxygen and fluorine gas which are bled into separate measuring tanks. The volumes of the tanks and the lines between the remotely operated valves are known. Therefore the desired weights of fluorine and oxygen in the measuring tanks are readily obtained from the measured gas temperatures and the set pressures. The run tank and propellant valve are maintained at -320°F in an insulated conditioning bath filled with liquid nitrogen. Prior to running, the prop valve, run tank and oxidizer manifold are evacuated. The oxygen and fluorine safety valves are opened allowing the gases to condense into the run tank. Since the fluorine and oxygen are condensed into a closed system, the problem of unequal boil-off changing the Flox percentage composition is avoided. It is expected that the turbulence caused by the condensation process, natural convection, the high miscibility of O_2 and F_2 and the short time between preparation of the mixture and firing of the engine (usually less than 10 minutes) prevent any significant stratification of the oxidizer mixture in the run tank. The operation is monitored by visually observing the measuring tank pressures on absolute pressure gauges. Because the regulator delivery pressure on the fluorine bottle is limited, the fill operation is repeated. The two charge/condense cycles provide the proper amount of 70/30 Flox for 200 msec of steady state operation. Figure 9 shows the pressure vs temperature settings required to produce the desired Flox weight in the run tank. After each run the manifold, run tank and propellant valve are purged with helium. This system provides the vacuum fill of Flox up to the propellant valve seat thus eliminating the problem of entrapped gases which could influence start transients. The same system and methods apply for OF_2 except that only the fluorine measuring tank is used.

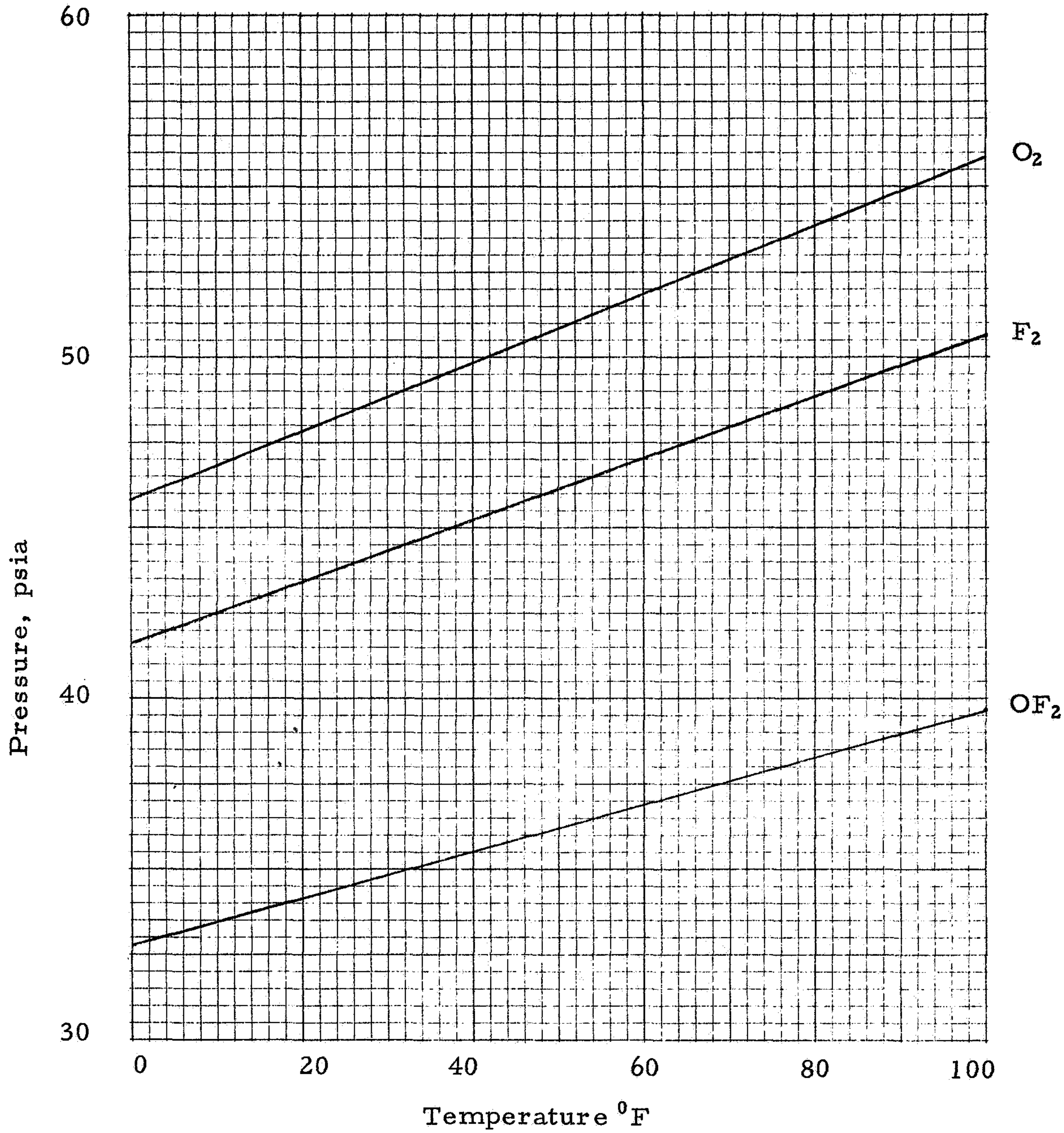


Figure 9. Flox System Pressurization Curves

3. Helium Pressurizing Systems

Separate helium systems pressurize the propellant tanks to the levels required for steady state design flow under the various test conditions.

Helium is used rather than nitrogen because it is less soluble in diborane (Ref. 6). Separate systems are used for the oxidizer and fuel tanks to provide safety through isolation, and flexibility of control. Referring to Fig. 8, both systems are identical. Each contains a regulated helium supply, safety valve, charge valve, vent valve and check valve to prevent back flow into the supply.

A similar arrangement provides the helium required for the diborane purge.

4. Temperature Conditioning Systems

The conditioning of the propellants is described above in Sections III. B. 1 and 2 for the fuel and oxidizer respectively.

The injector/chamber assembly was thermally conditioned to +70°, 0°, -100° and -200°F for the various runs. For the -100°F runs, crushed dry ice was placed in the chamber conditioning bath and the runs were made after the engine temperatures stabilized at the -100°F dry ice temperature. The +70°F runs usually required no conditioning at all since hardware temperature in the test stand was nominally 68°F. For the 0°F and -200°F runs, advantage was taken of the long thermal time constant of the heavyweight assembly. The 0°F runs were made by placing dry ice in the chamber bath and firing the engine at 0 ± 3°F as it cooled down to -100°F. For the -200°F runs, the hardware was first chilled to -100° with dry ice. Additional cooling was accomplished with liquid nitrogen chilling the dry ice and hardware to about -220°F. The engine was fired at -200° ± 3°F as it warmed up to restabilize at -100°.

Figure 10 shows the run tanks and prop valves (decoupled from the upstream system and without their conditioning baths) connected to the injector/chamber assembly which is mounted in the thrust chamber conditioning bath.

Figure 11 shows a front view of the Flox/diborane altitude ignition test system installed in test stand S12 Bay C. The photo shows the vacuum ignition test module suspended from an overhead hoist and

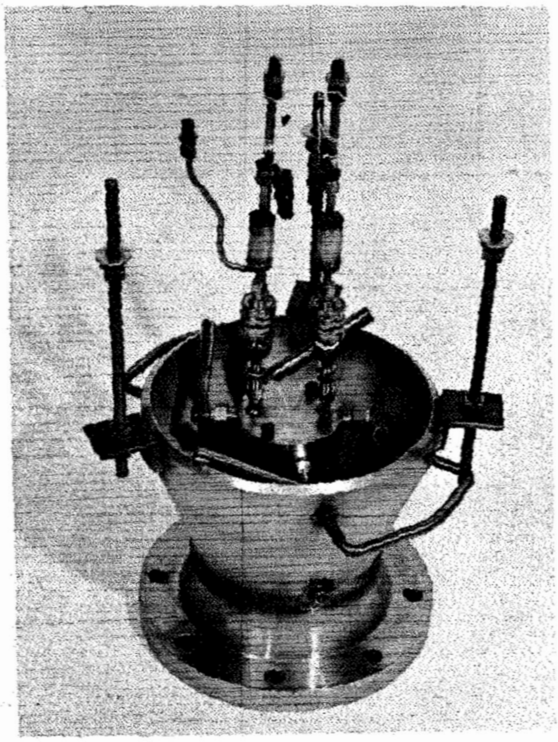


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Figure 10

Thrust Chamber Assembly Mounted in Bath

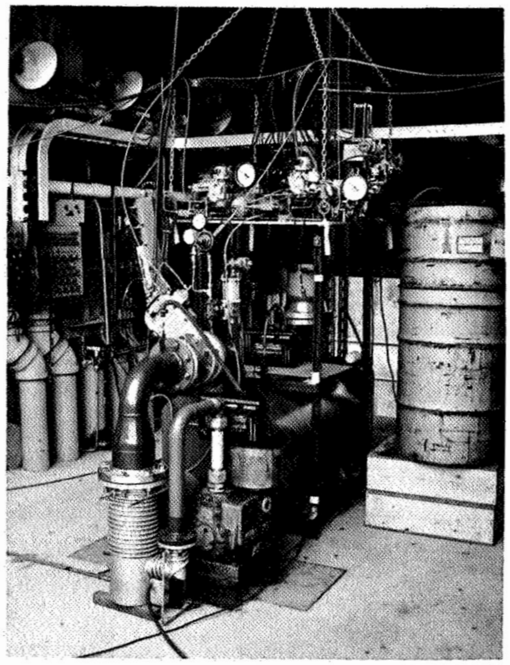

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Figure 11

Front View Test Stand S12C Installation

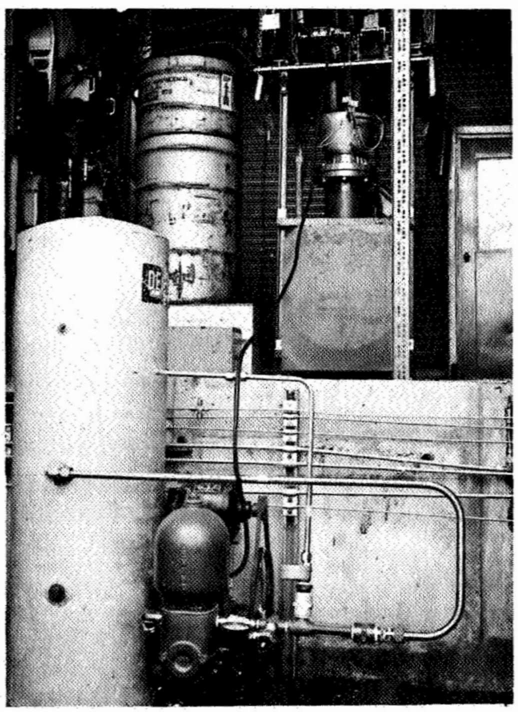

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Figure 12

Back View Test Stand S12C Installation

supported by four frame posts. The thrust chamber bath assembly is mounted on the altitude chamber and connected to the module. The diffusion pump and mechanical pump are in the foreground and the diborane tank is on the left.

Figure 12 shows the rear view. The scrubber system is in the foreground.

Figure 13 shows a close-up of the ignition module coupled to the injector/chamber and mounted in the thrust chamber bath. The run tanks and propellant valves are in the insulated conditioning baths immediately above the injector.

The critical system volumes are summarized in Table II.

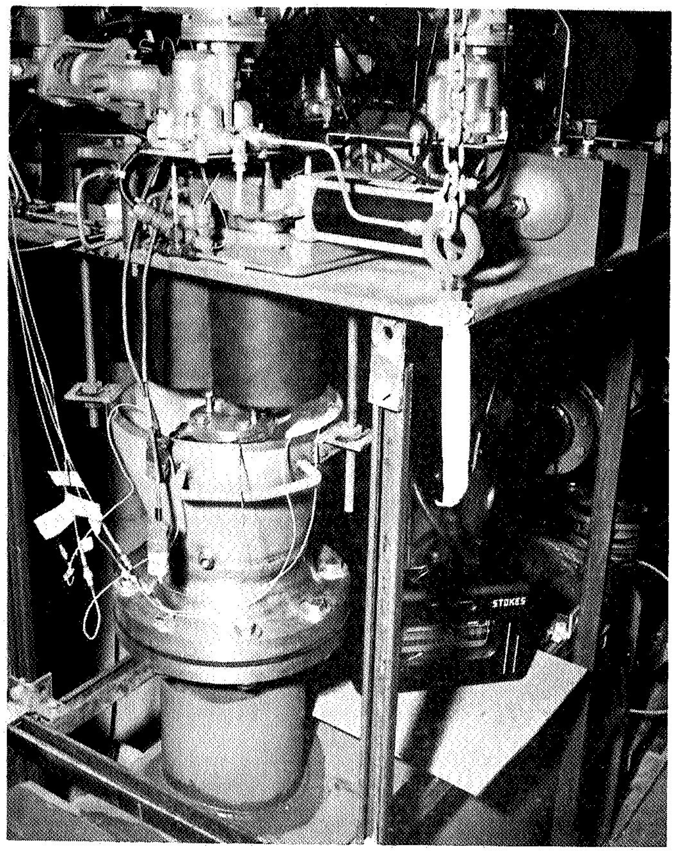
TABLE II

SUMMARY OF SYSTEM VOLUMES

Fluorine System (gas)	138.22 in.^{3}
Oxygen System (gas)	62.00 in.^{3}
OF_2 System (gas)	138.22 in.^{3}
Oxidizer Helium Pressurizing Line	1.53 in.^{3}
Oxidizer System (upstream of prop valve)	1.98 in.^{3}
Oxidizer System (downstream of prop valve)	--
9 Pair Injector	.138 in.^{3}
1 Pair Injector	.081 in.^{3}
Fuel Helium Pressurizing Line	1.38 in.^{3}
Fuel System (upstream of prop valve)	1.69 in.^{3}
Fuel System (downstream of prop valve)	--
9 Pair Injector	.154 in.^{3}
1 Pair Injector	.095 in.^{3}

C. INSTRUMENTATION

The location of much of the system monitoring instrumentation is indicated in Fig. 8. Visual gauges mounted on the storage gas bottles show supply and regulated pressures. Separate absolute pressure visual gauges show the pressure in each of the two calibrated Flox and OF_2 tanks. System temperatures are measured by copper-constantan thermocouples and monitored with a seven position manual switch and digital read-out.



5334 5

Figure 13

Close-Up of Test Installation

Four Kistler pressure transducers measure fuel and oxidizer injector manifold pressures and chamber pressures. The two chamber pressure transducers have different ranges both to detect initial propellant entry prior to ignition and to measure ignition starting transients. The Kistler chamber pressure transducers were coated with GE RTV Adhesive Sealant to delay heating (or cooling) of the transducers which would otherwise cause a zero shift. The coatings had to be replaced frequently due to erosion during the runs.

The Kistler pressure transducer outputs were conditioned by Model 566 Kistler charge amplifiers and displayed on a Tektronix dual beam oscilloscope with two type C-A amplifiers to show all four signals simultaneously. Polaroid pictures provide a permanent record of the start transient. Frequency response of the Kistler pressure measurements is well in excess of 25 kHz.

Valve voltage and current are monitored on a direct print recording oscillograph. Altitude chamber pressure is measured prior to each run with a Stokes-McLeod gauge and continuously monitored with a strain gauge and digital read-out.

The instrumentation is summarized in Table III.

TABLE III

INSTRUMENTATION FOR VACUUM IGNITION TESTS

Parameter	Transducer	Primary Read-out
Chamber Pressure	Kistler 603A (high gain)	Oscilloscope
Chamber Pressure	Kistler 603A (low gain)	Oscilloscope
Injector Manifold Press (2)	Kistler 603A	Oscilloscope
Propellant Temp (2) (run tank)	c/c Thermocouple	Indicating
Fuel Bath Temp	c/c Thermocouple	Indicating
Ox Temp in Measuring Tank (2)	c/c Thermocouple	Indicating
Injector Temperature	c/c Thermocouple	Indicating
Chamber Temperature	c/c Thermocouple	Indicating
Valve Current (2)	-----	Oscillograph
Valve Voltage (2)	-----	Oscillograph
Altitude Pressure	Stokes-McCleod Gauge	Indicating
Altitude Pressure	Teledyne 2545A (0-15 psia)	Indicating
Tank Pressure (2)	Bourdon Tube Gauge	Indicating
Ox Measuring Tank Press (2)	Bourdon Tube Gauge	Indicating

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IV. EXPERIMENTAL RESULTS

A. IGNITION TEST RESULTS

Forty-eight vacuum ignition test runs were conducted during the test program. Thirty of these runs were made with flox/diborane, sixteen with OF_2/diborane and one each with singly flowed OF_2 and diborane. All runs were initiated at a pressure altitude in excess of 250,000 feet. The conditions under which these runs were made, the propellant valve opening times, fuel manifold liquid fill times and ignition times are presented in Table IV. Photo reproductions of the oscilloscope traces from the four Kistler pressure transducers are given in logical groupings. Figures 14 through 18 show the bipropellant runs and Figure 19 shows the singly flowed propellant runs. In all cases, the time base is 10 milliseconds per centimeter. The traces in ascending order are: low sensitivity chamber pressure, oxidizer manifold pressure, high sensitivity chamber pressure and fuel manifold pressure. Calibration information to coordinate with test run numbers is given in Table V.

The chamber pressure traces of the figures all too often show an apparent pressure decrease with time after ignition. The apparent decay is, in reality, a zero shift downward caused by heating of the transducer diaphragm by the combustion products. (Diaphragm cooling causes an upward zero shift). The RTV coating used on the transducers (Sec. III. C) was successful in delaying the onset of thermal effects but the lifetime of the coatings was short and they had to be replaced frequently.

B. DEPOSITED COMBUSTION RESIDUE

Deposits were noted when the 100 psia design chamber and nine pair doublet injector were removed from the altitude chamber following Run 18. The entire interior of the altitude chamber, nozzle exit, interior of the thrust chamber and face of the injector were covered with a medium grey powder. The powder had a smooth mat finish. Small globules of grey with a silvery appearance about .03 in. in diameter were dispersed on the surface. The deposit was .03 to .06 in. thick on the nozzle exit. Upon exposure to air, the color of the powder changed from medium to dark grey indicating that the deposit was hydroscopic or that a chemical reaction took place. Two samples were taken. Sample No. 1 was collected from the nozzle extension and mounting flange. Sample No. 2 was collected from the injector face and the interior of the thrust chamber. Both samples were removed with wooden spatulas and placed in nitrogen atmospheres in separate sample jars.

TABLE IV. TEST DATA SUMMARY

HARDWARE			OXIDIZER				FUEL - DIBORANE						
Injector Type	Design Chamber Pressure psia	Hardware Temp. °F	Type	Temp. °F	Tank Set Pressure psig	Prop. Valve Full Open msec	Temp. °F	Tank Set Pressure psig	Prop. Valve Full Open msec	Manifold Fill Time msec	Propellant Lead	Ignition Time msec	Run No. S12CX
9 pair	100	70	Flox	-320	164	15.5	-100	174	15.5	-	None	24	5
"	"	0	"	"	"	16.5	"	"	21	-	"	23	18
"	"	-100	"	"	"	16	"	"	-	23.5	"	22	10
"	"	-200	"	"	"	16.5	"	"	15.5	23	"	21	17
"	"	70	"	"	"	16	"	"	28	-	Ox	26	7
"	"	0	"	"	"	13	"	"	29.5	-	"	32	13
"	"	-100	"	"	"	13	"	"	27	35	"	33	12
"	"	-200	"	"	"	17	"	"	29.5	36	"	33	14
"	"	70	"	"	"	28	"	"	15.5	-	Fuel	40	6
"	"	0	"	"	"	22.5	"	"	15	-	"	--	16
"	"	-100	"	"	"	28	"	"	14.5	23	"	35	11
"	"	-200	"	"	"	23	"	"	15	23	"	53	15
1 pair	"	70	"	"	142	15.5	"	153	15.5	-	None	18	19
"	"	0	"	"	"	15	"	"	15	-	"	37	25
"	"	-100	"	"	"	18	"	"	15	20	"	20	20
"	"	-200	"	"	"	17.5	"	"	15	20	"	22	28
"	"	70	"	"	"	11.5	"	"	24	-	Ox	30	23
"	"	0	"	"	"	12	"	"	25.5	-	"	30	26
"	"	-100	"	"	"	13	"	"	27	32	"	30	22
"	"	-200	"	"	"	18	"	"	28	32.5	"	~27	29
"	"	70	"	"	"	25	"	"	14	-	Fuel	36	24
"	"	0	"	"	"	26	"	"	14	-	"	26	27
"	"	-100	"	"	"	24	"	"	13	19.5	"	53	21
"	"	-200	"	"	"	28	"	"	15.5	20	"	32	30
9 pair	"	70	OF_2	"	150	17	"	174	16.5	-	None	25	31
"	"	0	"	"	"	18	"	"	17	-	"	25	32
"	"	-100	"	"	"	16.5	"	"	16	23	"	27	33
"	"	-200	"	"	"	17	"	"	17	23	"	27	34
"	"	-100	"	"	"	16	"	"	29	38	Ox	33	37
"	"	-100	"	"	"	29	"	"	15.5	25	Fuel	37	35
"	"	-100	"	"	"	16	- 10	202	17	-	None	45	44
"	"	-100	"	-170	172	18	"	"	22	-	"	25.5	46
"	"	-100	"	-150	"	18	-100	174	17	24	"	26	45
"	20	70	"	-320	70	15	"	94	14	-	"	29.5	39
"	"	0	"	"	"	15	"	"	14	-	"	30.5	40
"	"	-100	"	"	"	13.5	"	"	14	-	"	28.5	43
"	100	"	"	"	150	14	NA	0	NA	-	NA	27	48
"	"	"	None	NA	0	NA	-100	174	15.5	23.5	NA	--	47

Explanation

- Propellant lead is controlled by delaying application of valve voltage to the appropriate second valve using a relay having a transfer time of 0.01 ± .001 sec.
- Fuel manifold fill times are obtained from water hammer peaks in the manifold pressure traces. The absence of data indicates that water hammer peaks were not observed.
- Valve poppets unseat at 5 ± 1 msec after application of valve voltage in all tests.
- Time is referenced from time of voltage application to the leading propellant valve.

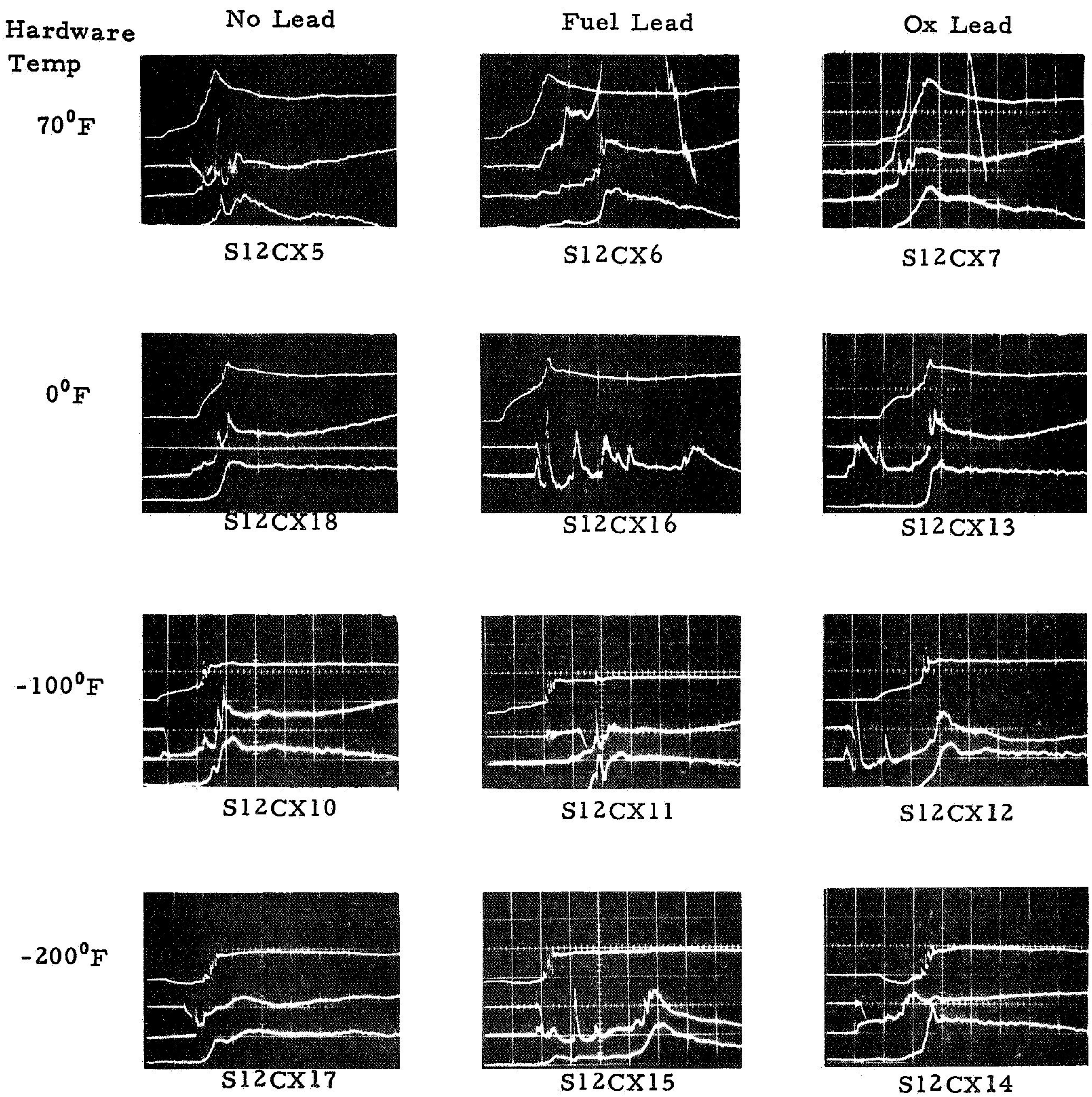


Figure 14. Oscillograms of Ignition Tests with Flox/Diborane, 9 Pair Injector, 100 psia Chamber

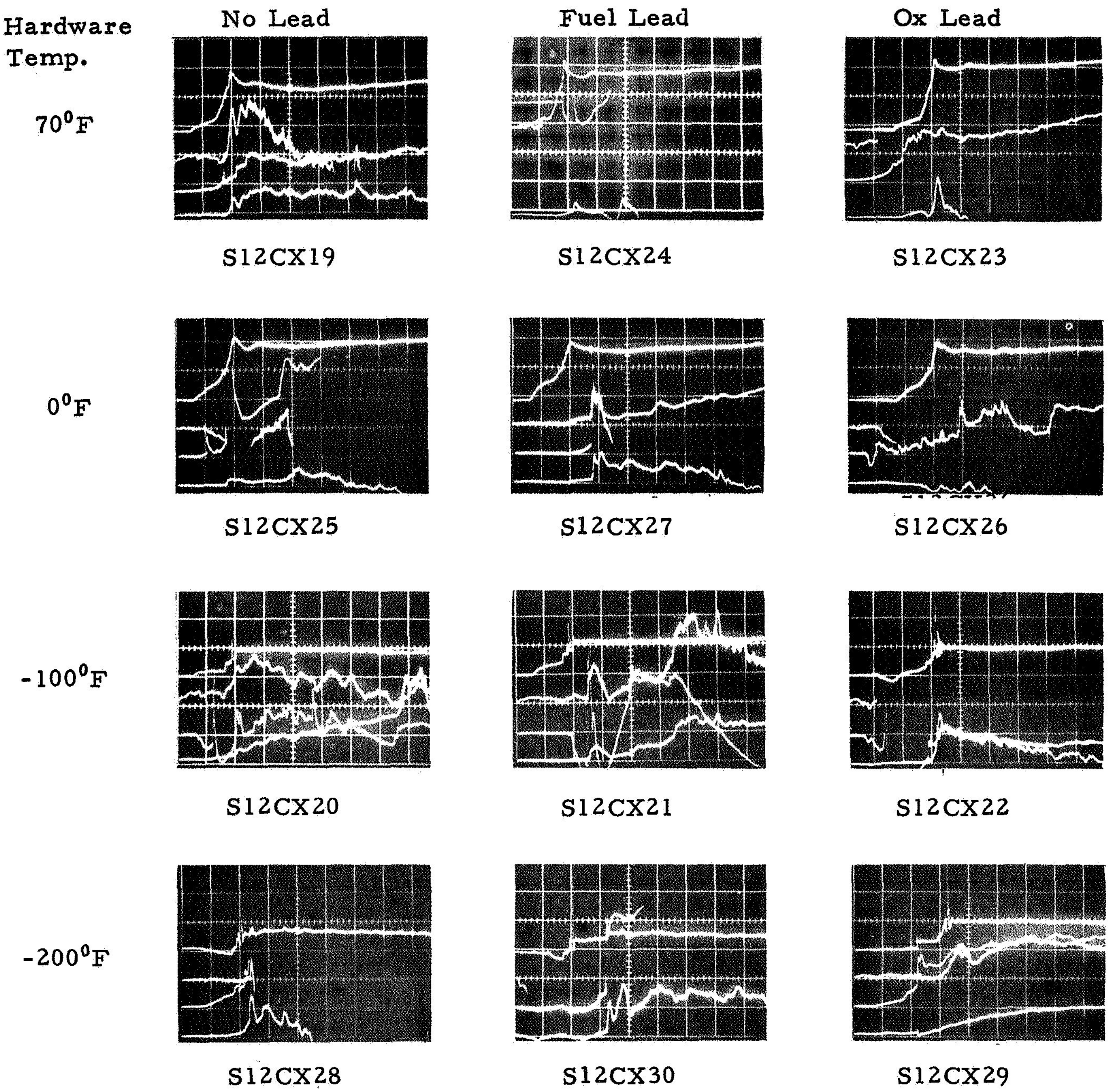


Figure 15. Oscillograms of Ignition Tests with Flox/Diborane, 1 Pair Injector, 100 psia Chamber

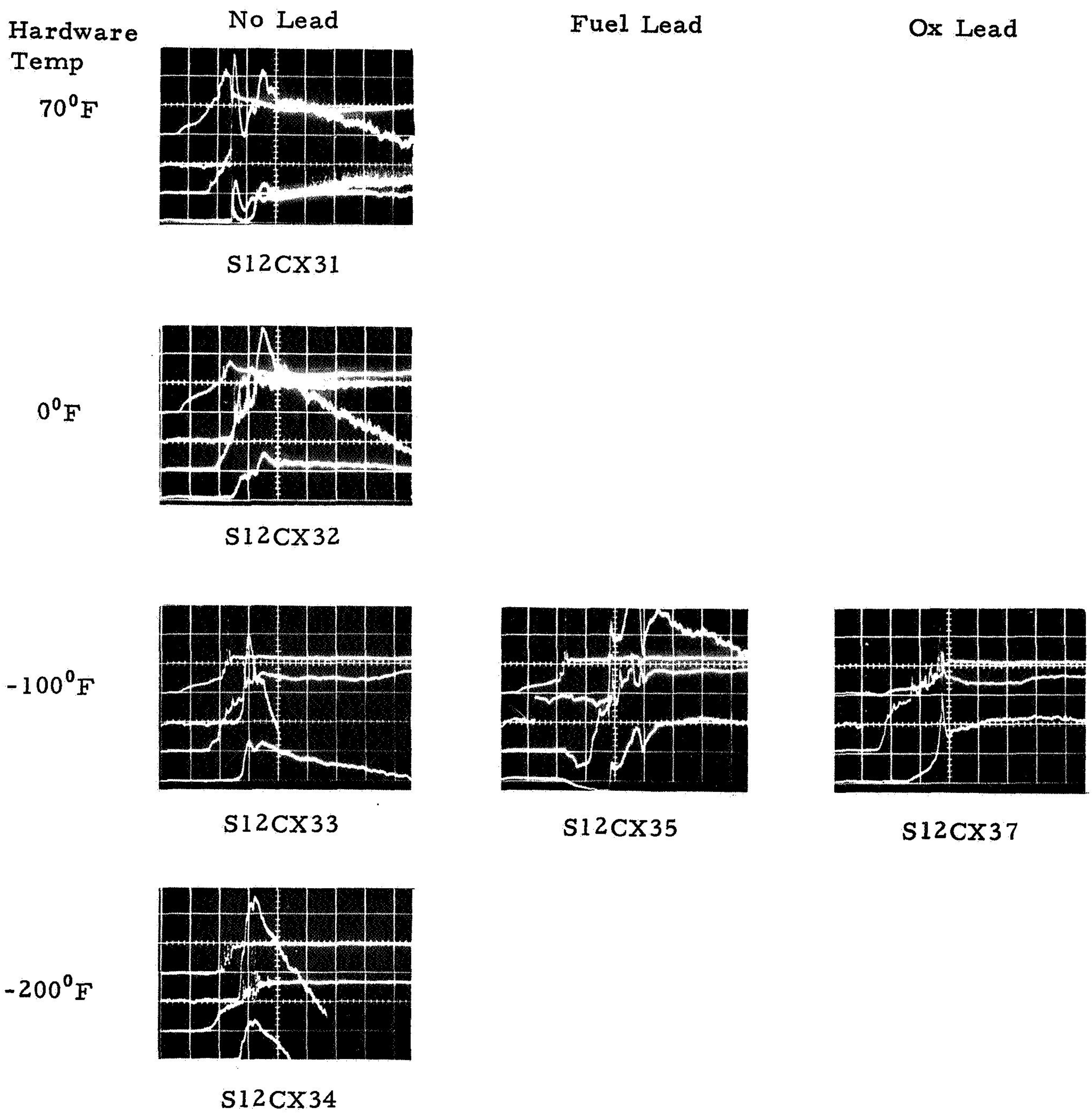
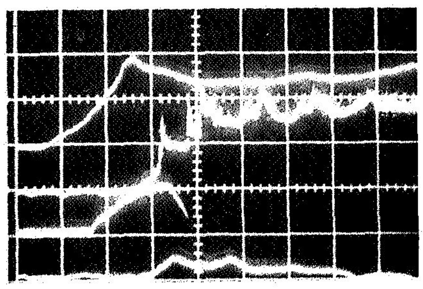


Figure 16. Oscillograms of Ignition Tests with OF_2/Diborane, 9 Pair Injector, 100 psia Chamber

No Lead

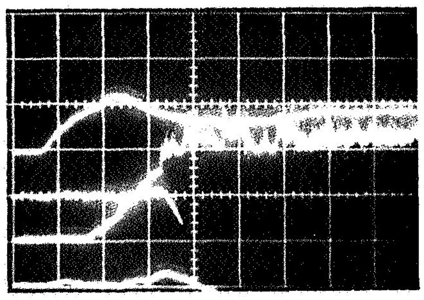
Hardware Temp

70^0F



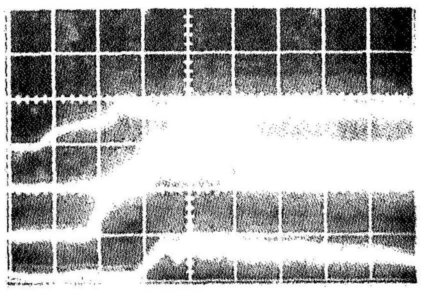
S12CX39

0^0F



S12CX40

-100^0F



S12CX43

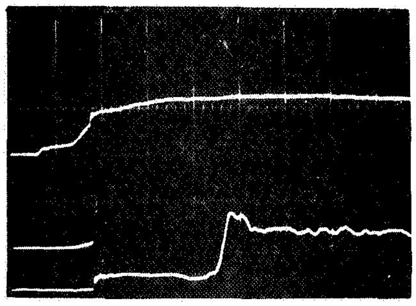
Figure 17. Oscillograms of Ignition Tests with OF_2/Diborane, 9 Pair Injector, 20 psia Chamber

Hardware Temp

No Lead

Propellant Temp

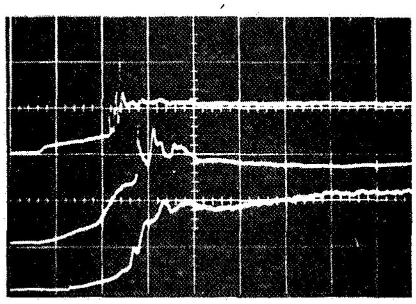
-100°F



-10°F B_2H_6
-320°F OF_2

S12CX44

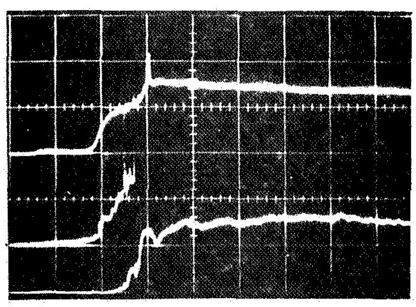
-100°F



-100°F B_2H_6
-150°F OF_2

S12CX45

-100°F



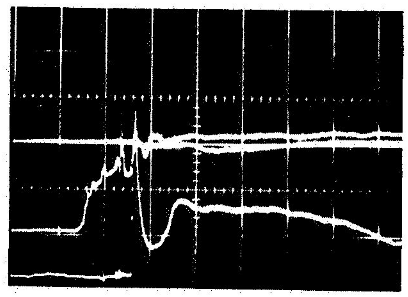
-10°F B_2H_6
-170°F OF_2

S12CX46

Figure 18. Oscillograms of Ignition Tests with OF_2/Diborane, 9 Pair Injector, 100 psia Chamber, Warmed Propellants

Hardware Temp | Propellant Temp

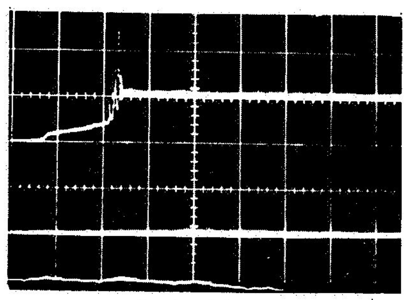
-100°F



-320°F OF_2

S12CX47

-100°F



-100°F B_2H_6

S12CX48

Figure 19. Oscillograms of Singly Flowed Propellant Tests with OF_2 and Diborane, 9 Pair Injector, 100 psia Chamber

TABLE V

TRANSDUCER CALIBRATION INFORMATION FOR FIGURES 14 - 19

Trace	Quantity Measured	Calibration psia/cm	Test Runs
4	Fuel Manifold Pressure	156	1 - 48
3	High Sensitivity Chamber Pressure	9	1 - 18
		26.3	19 - 48
2	Ox Manifold Pressure	134	1 - 24
		50.25	25
		105	26 - 48
1	Low Sensitivity Chamber Pressure	93	1 - 24
		186	25
		93	26 - 37
		37.2	38 - 43
		93	44 - 46
		37.2	47, 48
	Time base all traces	10 msec/cm	

Two types of analyses were performed on the samples: spectro analysis and X-ray diffraction analysis. The major components were found to be amorphous elemental boron, B_2O_3, H_3BO_3 and Fe_3O_4. The results of the analyses are presented in Table VI. The oxides of boron are a natural result of the combustion process following cooling to room temperature or below. The reason for the presence of elemental boron is not as readily apparent. It is probable that it resulted from the fuel rich tail-off at the end of a pulse and possibly from pyrolysis of excess diborane on the warm engine surfaces. The fuel tank was sized for warm propellant and since the filling method did not allow for partially filling the tank, low temperature runs had excess diborane which resulted in a fuel rich tail-off.

During the test program, the injectors were periodically removed from the system and cleaned. Runs 1, 19, 25, 27, 30, 31, 35, 38, 41 and 44 were made with clean injectors.

The significance of the deposit was clearly demonstrated in the singly flowed OF_2 test. Run 47 (Fig. 19) was made to obtain information on oxidizer transport times and vaporization levels in the absence of combustion. Approximately 27 msec after signal voltage was applied to the oxidizer propellant valve, a high level chamber spike occurred. The amplitude was at least 150 psia. This was followed by a period of essentially constant chamber pressure of 35 psia (See Fig. 19). Since there was no diborane in the fuel tank and the fuel propellant valve was not actuated, it is assumed that the OF_2 reacted with the residue deposited on the injector face and thrust chamber wall during the preceding three hot firings.

C. POPPET COCKING OF PROPELLANT VALVES

All tests were conducted with in-line, solenoid-operated, metal-seated propellant valves designed for LF_2 service (Sec. III. A. 3). The current traces exhibit first a small perturbation at about 5 msec after voltage application, start of poppet transfer at about 11 msec and valve full open at about 16 msec. Since manifold pressure generally showed a slight increase at about 6 msec, it appears that the first small perturbation of the current trace reflects an unseating of the valve poppet although actual transfer does not start for another 5 - 6 msec. A typical fuel valve current trace and fuel manifold pressure trace (based on Run 5, Fig. 14) are shown in Figure 20. The manifold pressure trace first rises at approximately 6 msec. (The remainder of the pressure trace is discussed in Sec. V).

The oxidizer propellant valve exhibited the same characteristic but the occurrence was sporadic and the amplitude of the resultant manifold pressure was lower. The valve manufacturer believes that the poppet cocking condition

TABLE VI. COMBUSTION PRODUCTS RESIDUE ANALYSIS

Thiokol CHEMICAL CORPORATION
REACTION MOTORS DIVISION
DENVILLE, NEW JERSEY

MAR No. 0360

RESEARCH ~~METALLURGY~~ DEPARTMENT – MATERIALS ANALYSIS REPORT

LOG NO. 8-0206 8-0207 PROJ. No. 5534-38-5001 SUBMITTED BY OR DEPT. NO. G. Mistler DATE 8/8/68

MATERIAL Solids from Run No. S12 C~~X~~18

ANALYSIS REQ'D. Identify DATE REQUIRED

Spectro Analysis	No. 1	No. 2				No. 1	No. 2		
Mg	T	ND			C				
Al	L	ND			P				
Si	T	FT			S				
Ti	FT	ND			N				
V					O				
Cr	T-L	T			Se				
Mn	T-L	FT			Be				
Fe	M-H	L			B	H	H		
Co					Li				
Ni	T	T			Na				
Cu	FT	ND			K				
Zn					Ca				
Zr					Ba				
Hf					Sr				
Mo	T	T			As				
Nb					Cd				
Ta					Ag				
W					Sb				
Th					Sn				
Pb					Bi				

X/Ray Diffraction:

No. 1 Major constituent - Elemental Boron (amorphous)

also B_2O_3, H_3BO_3, Fe_3O_4

No. 2 Major constituent - Elemental Boron (amorphous)

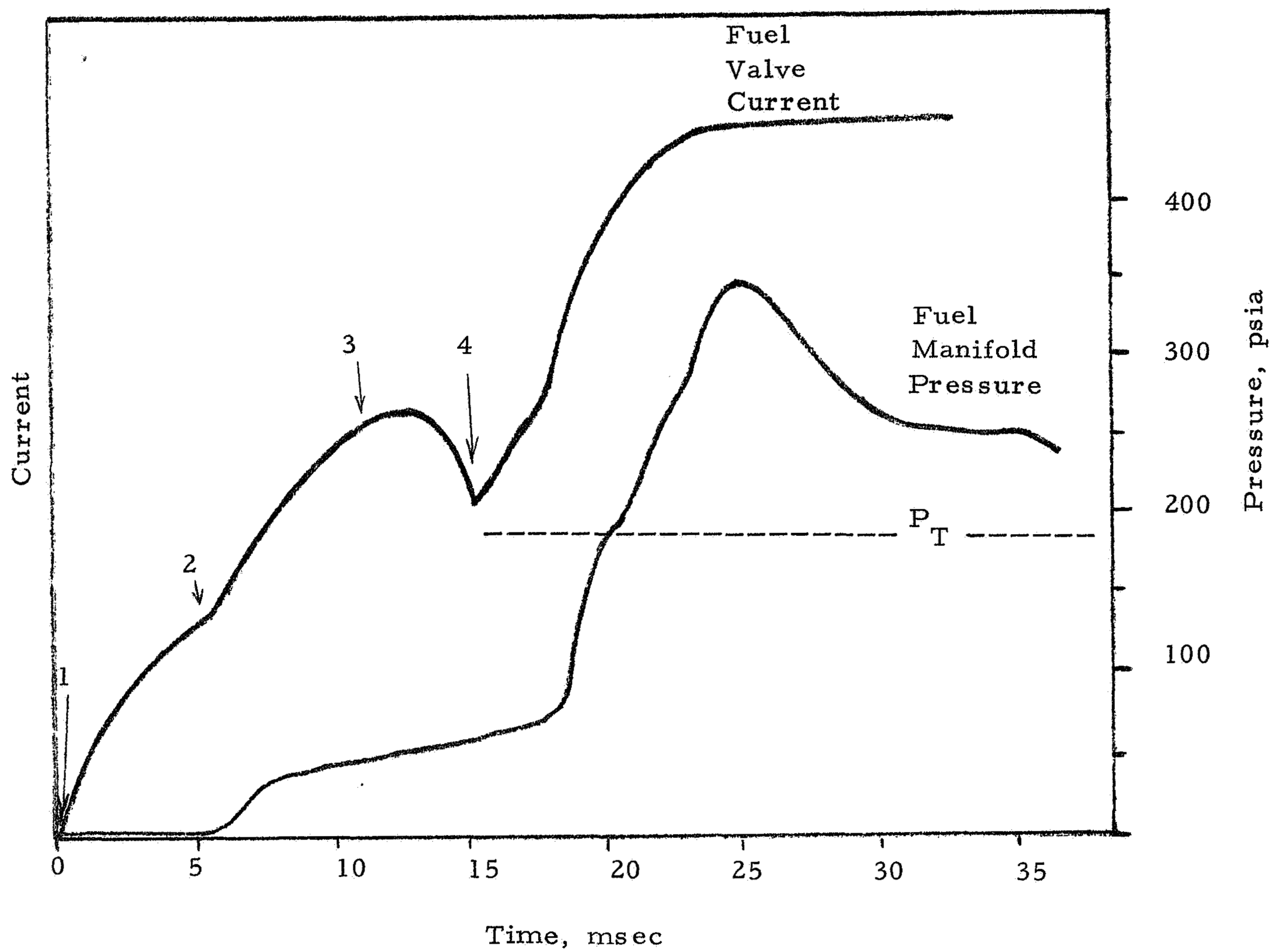
also B_2O_3, H_3BO_3

Sample No. 1 contained a considerable quantity of magnetic material (Fe_3O_4)

REMARKS: No. 1 from Nozzle Extension + Mounting Flange
No. 2 from Injector + Thrust Chamber Walls

HIGH = H > 10%
MEDIUM = M 1% - 10%
LOW = L .1 - 1%
TRACE = T .01% - .1%
FAINT TRACE = FT < .01%
NOT DETECTED = ND

TESTED BY B. Fagan APPROVED DATE 8/12/68



1. Voltage applied to valve

2. Poppet Unseats

3. Poppet starts to transfer

4. Valve full open

Figure 20. Valve Coil Current and Fuel Manifold Pressure vs Time

can be eliminated by reducing the clearance in the poppet guide shaft.

D. HARDWARE CONDITION

The hardware was carefully examined after completing the 48 altitude ignition test runs and no evidence of any burning, pitting or erosion was found. The condition can best be described as "like new." The same remarks can be made about the entire system but with two minor exceptions. There were two instances of metal burning and both involved Kistler pressure transducers. The Model 701A Kistler transducer used to monitor pre-ignition chamber pressure had a small hole burned through the diaphragm. It was removed from the chamber following Run 18 and replaced by a 603A set with a high gain. A similar failure occurred with the Kistler Model 603A located in the oxidizer manifold. The transducer was removed following Run 24 and replaced by another 603A. Both damaged transducers were repaired by the manufacturer by simply replacing the burned diaphragms.

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V. DISCUSSION OF RESULTS

In this section, the more significant findings and potential problems which were uncovered during the investigation are discussed first. Then the effects of the programmed variables are described.

A. SIGNIFICANT FINDINGS AND POTENTIAL PROBLEMS

In general, ignition pressure transients in the thrust chamber were smooth. However, anomalous pressure fluctuations in the oxidizer manifold were common and these frequently affected the ignition delay times markedly. Only one severe ignition pressure spike was observed in the chamber. Particulars are discussed in the following paragraphs.

1. Chamber Pressure Transients

Ignition transients were generally smooth in both the 100 psia and 20 psia design chamber pressure engines. Chamber pressure exhibited fast rise times and little overshoot for most cases of simultaneous propellant entry and oxidizer lead. However ignition was rougher with a fuel lead and in those runs exhibiting a high level of oxidizer manifold pressure excursions (see below).

Only one chamber pressure spike was observed during the program. It occurred with OF_2 and with an oxidizer lead (Run 37, Fig. 16). It was the only run made with an OF_2 lead although eight tests were made with a Flox lead. Considering the results of the singly flowed OF_2 test (Run 47, Fig. 19) where the OF_2 reacted with deposited residue (Sec. IV.B), there is the strong possibility that the chamber pressure spike is due to reaction with previously deposited residue. The conditions (OF_2 lead, 100 psia chamber, 9 pair injector and -100°F hardware) were the same in both cases. The differences were that in the singly flowed OF_2 run, the spike occurred at 27 msec while in the bipropellant run, the spike occurred at 37 msec. This is approximately 1 msec after water hammer spikes indicate that the fuel manifold was full. The amplitude was also more than twice that of the singly flowed propellant run.

There was no evidence in any run of combustion instability during the ~50 msec that chamber pressure was monitored. However two types of periodic pressure perturbations were recorded in some runs by the high response chamber pressure transducers. Low frequency chamber pressure oscillations of about 80 Hz were observed in the 20 psia chamber (see for example Run 39, Fig. 17). The wave shape of the oscillatory pressure trace is not the well known fast-rise, exponential decay type normally associated with insufficient injector impedance but is a damped sinusoidal wave which reflects cyclic pressure variations occurring in the oxidizer manifold. This is confirmed by the relative pressure amplitudes: ±30 psi in the manifold, ±4 psi in the chamber.

High frequency chamber pressure oscillations, estimated to be approximately 5 kHz, are evident in Runs 31 and 32 (Fig. 16). These too are reflected disturbances emanating from the oxidizer manifold and will be discussed in the following sections.

2. Oxidizer Manifold Transients

Three types of oxidizer manifold pressure fluctuations were observed: random pressure peaks, high frequency pressure oscillations (roughly 5 kHz) and low frequency pressure oscillations (roughly 80 Hz).

a. Random Pressure Peaks

Random pressure peaks in the oxidizer manifold were observed to some extent in most runs but pronounced effects on ignition occurred less frequently. In some cases, the pressure peaks exceeded 500 psia (e.g. Runs 21 and 22, Fig. 15). In other cases, the manifold pressure trace vanished completely indicating a steep-faced, high pressure transient (e.g. Runs 23-25, 30, 44 and 46, Figs. 15 and 18). Runs 21-30 were made with the single element injector with Flox as the oxidizer whereas Runs 44 and 46 were made with the nine pair injector with OF_2 as oxidizer and the diborane at the warmer temperature ($-10^{\circ}F$ vs $-100^{\circ}F$). Significantly, Runs 30 and 44 were made with clean injectors.

In general, the level of activity in the oxidizer manifold was greater with Flox than with OF_2 although the pressure fluctuations with the latter also impeded ignition in a number of cases. Manifold pressure peaking was also greater with the single element injector than with the nine pair injector, with a fuel lead rather than either no lead or an oxidizer lead, and somewhat higher with a previously run injector. The principal effect of the severe pressure peaks was to markedly increase the ignition delay time (often two-fold) by momentarily stopping or at least reducing the oxidizer throughput into the thrust chamber. No damage to the propellant valves or to the heavy-duty injectors was experienced from the pressure peaks although this remains a distinct possibility, especially in flight-weight hardware.

The cause of the random pressure peaking must be reaction between the oxidizer and foreign materials in the manifold. Two types of foreign material in the oxidizer manifold appear to be involved: unreacted fuel and combustion residue. The fact that pressure peaking is worse with a fuel lead and the fact that clean injectors are susceptible to pressure peaking both indicate that unreacted fuel enters the oxidizer manifold after the fire signal but prior to initiation of oxidizer flow. The premature cocking of the propellant valve in the fuel system (Sec. IV. C) probably aggravates the situation somewhat but is not believed to be the sole cause.

The fact that pressure peaking is worse with a previously run injector and the fact that runs with an oxidizer lead are also somewhat susceptible indicate that combustion residues from prior pulses migrate back into the oxidizer manifold during the off-time between pulses. It was noted whenever the test system was disassembled for cleaning or a hardware change that a powder dispersion or colloidal suspension was present in the chamber. Particles could therefore migrate into the oxidizer manifold and become deposited on the inside walls. Reactivity between the oxidizer and combustion residue was clearly demonstrated (Sec. IV. B).

The greater susceptibility of the single element injector to manifold pressure peaking is to be expected due to the lower flow impedance of the single large diameter hole of $L/d = 6$ as compared to the nine smaller holes of $L/d = 12$.

b. High Frequency Pressure Oscillations

The high frequency pressure oscillations in the oxidizer manifold are clearly visible in Runs 31, 32, 39 and 40 (Figs. 16 and 17). They occurred only with OF_2/diborane at hardware temperatures of $+70^\circ$ and 0° and were observed in both the 20 psia and 100 psia chambers using the nine pair injector. (The single element injector was not tested with OF_2.) The phenomenon was not observed at hardware temperatures of $-100^\circ F$ and $-200^\circ F$ nor in any case with Flox in either injector. The oscillations start just after ignition and appear also on the high sensitivity chamber pressure traces. The pressure amplitude as recorded by the oxidizer manifold transducer is about ten times higher and contains higher frequency components than those recorded by the chamber pressure transducers. This indicates that the source of the oscillations is probably the oxidizer feed line, or more likely, the oxidizer manifold. The conditions which exist in the feed line and oxidizer manifold during the start transient are somewhat analogous to line "cool-down" transients associated with the transfer of cryogenic fluids. It is also similar to start-up transients in heat exchangers where the fluid vaporizes completely or partially in the lines. The condition continues until thermal equilibrium is reached. R. S. Thurston (Ref. 7) cites several papers in which acoustic phenomena are reported (Refs. 8-16). Thurston also provides analytical approaches to predict the oscillatory frequencies using conventional open-open pipe and Helmholtz resonator equations. The open-open pipe equation given by Thurston is:

$$F = \frac{\sqrt{g \gamma RT}}{2L} = \frac{a}{2L}$$

where F = frequency in Hz $\quad sec^{-1}$

a = acoustic velocity $\quad$ ft/sec

g = dimensional constant $\quad 32.2 \frac{lbm\text{-}ft}{lbf\text{-}sec^2}$

γ = ratio of specific heats

R = specific gas constant $\quad \frac{lbf\text{-}ft}{lbm\text{-}^\circ R}$

T = vapor temperature $\quad ^\circ R$

Figure 21 shows a section view of the oxidizer manifold in the nine pair injector. The OF_2 enters as indicated on the drawing. The flow divides going out the straight section between the two distribution manifolds. The Kistler pressure transducer mounts in the end of the straight section. Figure 22 shows a plot of frequency vs. temperature which results from applying the open-open pipe formula to the straight section of manifold. The calculated frequencies between 0° and $50^\circ F$ are approximately 5 kHz which is the value of the high frequency oscillations estimated from the data. Although acoustic phenomena offers an interesting approach, the cause of the high frequency oscillations is uncertain at present and further study is required.

c. Low Frequency Pressure Oscillations

Low frequency pressure oscillations in the oxidizer manifold were observed in Run 39 especially and in Run 40 (Fig. 17). This phenomenon was observed only with the 20 psia chamber with OF_2 as the oxidizer. (Flox has not been tested in the low P_{ch} chamber nor has the full

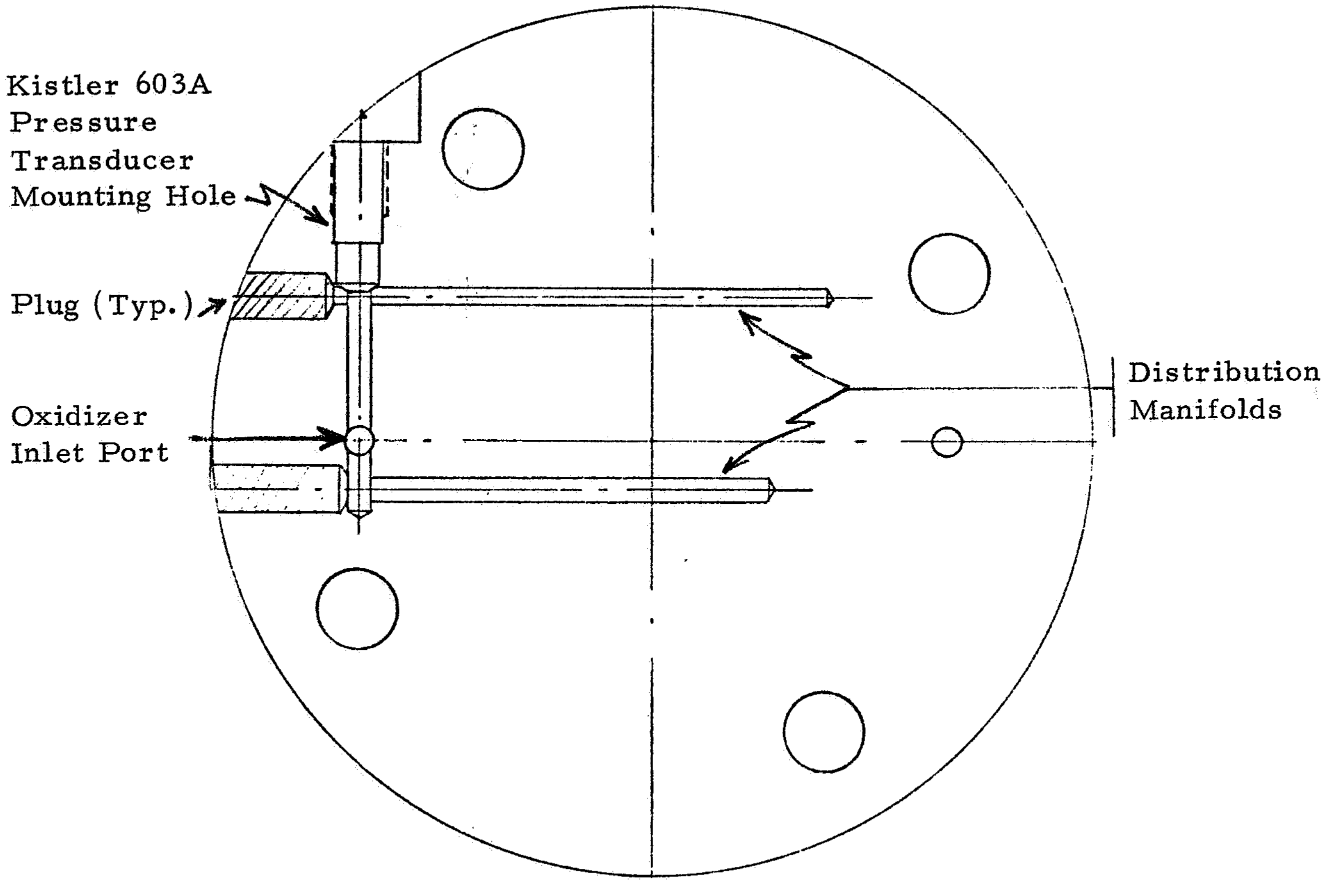

Figure 21. Nine Pair Injector - Oxidizer Manifold Section View

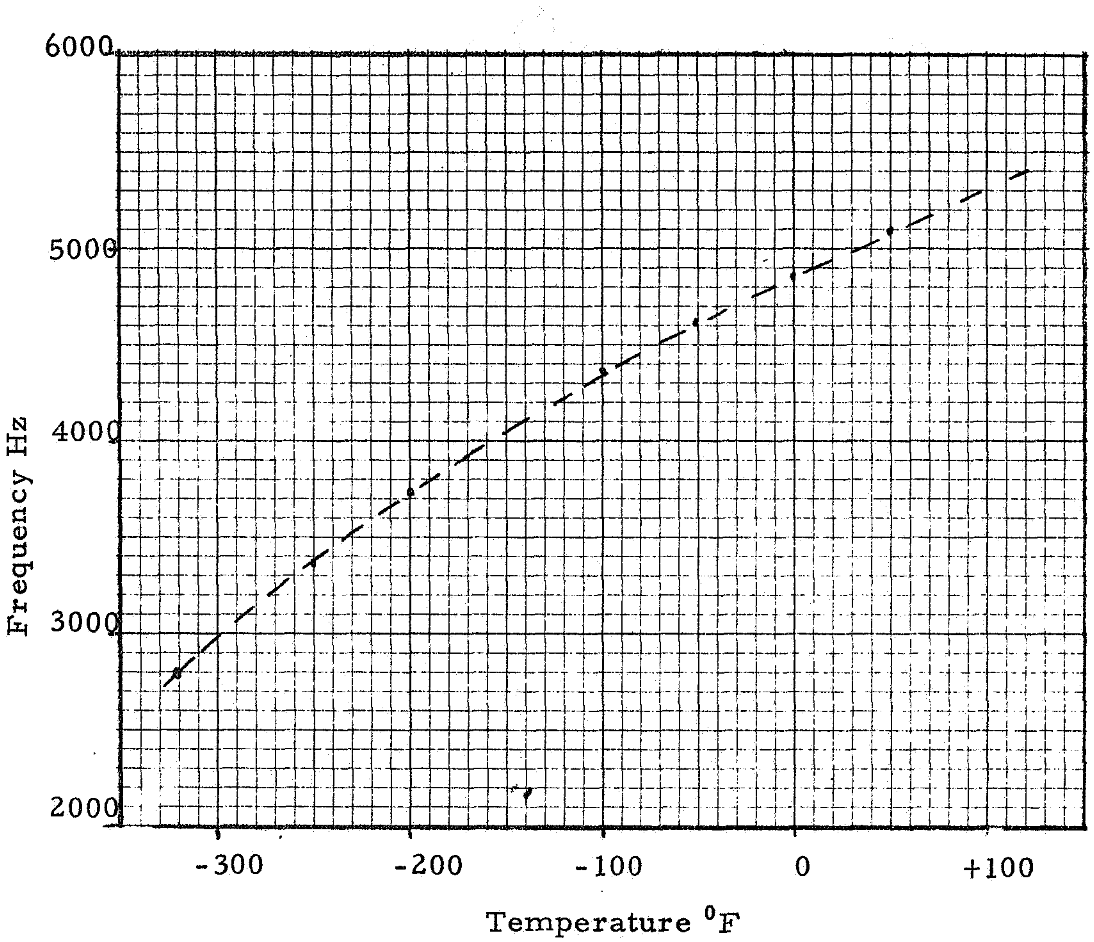

Figure 22. Oxidizer Manifold Section
Frequency vs Temperature

range of hardware temperatures been evaluated with OF_2 in the low P_{ch} chamber). The source of the low frequency oscillations (approx. 80 Hz) appears to be the oxidizer feed system/manifold where the amplitudes of the pressure oscillations are 7 to 8 times higher than chamber pressure variations. Also, the manifold oscillations continue after the chamber pressure variations have damped out. Further, since the design injector pressure drop is more than 50% of the operating chamber pressure, damping is critical and there should be no feedback between the supply lines and the chamber (Ref. 17). Further investigation is required.

d. Manifold Pressure Levels

It is tempting to consider in detail the DC component of the manifold pressure traces, however, the Kistler transducers in the manifolds were not thermally protected. Thus, whenever the propellant is cooler than the injector, a zero shift upward (indicating positive pressure) can occur. Since the oxidizer temperature was in every case lower than the hardware temperature (Table IV), all oxidizer manifold pressure traces are subject to positive zero shift.

B. EFFECTS OF THE PROGRAMMED VARIABLES

The parameters investigated are: oxidizer (Flox and OF_2), hardware temperature, propellant lead/lag, injector configuration, design chamber pressure and propellant temperature. These are discussed in the following paragraphs.

1. Flox-OF_2 Comparison

There was less pressure peaking in the oxidizer manifold with OF_2 than with Flox but high and low frequency oscillations occurred with the former. Engine ignition delays were generally longer with OF_2: 26 ± 1 msec vs 22.5 ± 1.5 msec for comparable Flox runs (Runs 31-34 and Runs 5, 18, 10 and 17, Table IV). These runs were made with no propellant lead, nine pair doublet injector, 100 psia chamber and at equivalent hardware temperatures. Comparable runs made with an oxidizer lead yielded 33 msec in each case. Runs made with a fuel lead produced an ignition delay time of 35 msec for Flox (Run 11) and 37 msec for OF_2 (Run 35).

2. Effect of Hardware Temperature

Hardware temperatures in the range +70°F to -200°F had very little effect on engine ignition delays. This result was obtained with both propellant combinations, both injectors and both chambers. In these tests, the oxidizer and its valve were conditioned to -320°F, the fuel and its valve to -100°F.

Despite the constant ignition delays, chamber/injector temperatures did strongly affect filling of the fuel injector manifold, as shown in Fig. 23. The figure is a composite of fuel manifold pressure traces of Flox/diborane tests conducted with the 100 psia chamber, both injectors and covering the full range of hardware temperatures. It is seen that at the two lowest hardware temperatures (-100°F and -200°F), water hammer pressure peaks are obtained indicating liquid filling of the injectors. The subsequent steady pressure levels are approximately at tank set pressures (Table IV).

In contrast to the low temperatures cases, tests with the hardware temperatures above the fuel temperature (-100°F) show no water hammer pressure peaks and, furthermore, exhibit manifold pressures in excess of tank set pressures. Manifold pressures pass through a "soft" peak and then decay gradually toward tank-set pressure. In these cases, full liquid filling of the injector appears not to be reached during the recorded run time. The cold propellant entering the relatively warm injector undergoes strong flashing and, following the initial, brief, all vapor flow period, passes through the injector orifices as a two-phase, vapor-liquid mixture. A measure of the time-dependent temperature of the propellant in the manifold can be obtained by taking the measured manifold pressure as the equilibrium vapor pressure of the fuel. However, the manifold pressure transducer is not thermally protected and therefore, in these runs, is subject to zero shift in the positive direction. Semi-qualitatively, then, the manifold pressure traces of Fig. 23 indicate that the fuel, which is initially at -100°F, is quickly warmed in the manifold to near 0°F (peak manifold pressure) but as the injector cools the incoming propellant is warmed somewhat less, e.g. to approximately -15°F at the end of the recorded data of the nine-element injector tests.

Liquid filling of the Flox injector was not observed, as expected, since the vapor pressure of Flox at the lowest hardware temperature tested (-200°F) is in excess of 500 psia.

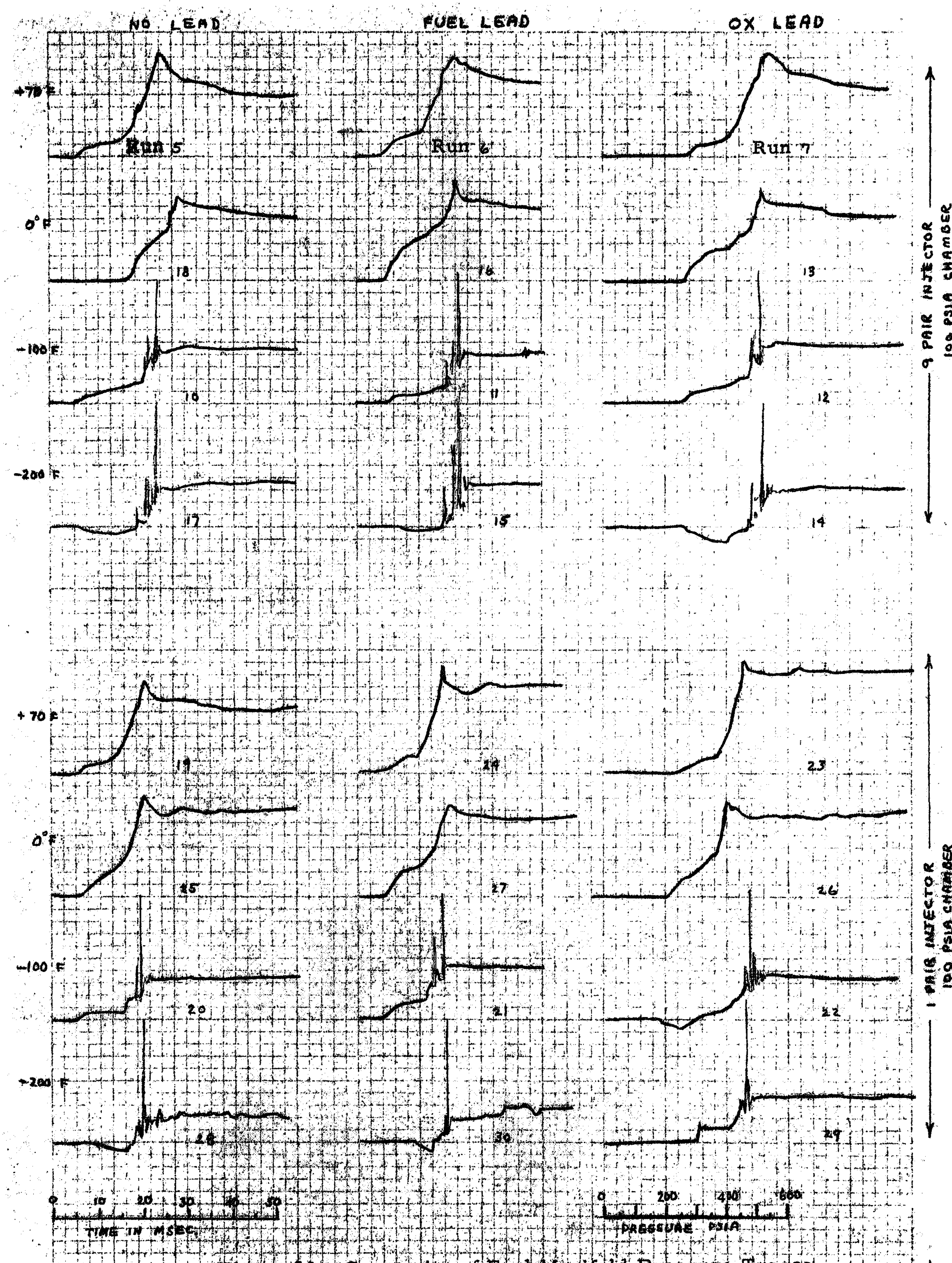

Figure 23. Composite of Fuel Manifold Pressure Traces of 24 Flox/Diborane Ignition Tests

In the one -200°F hardware test with OF_2 as oxidizer (Run 34, Fig. 16), oxidizer manifold liquid fill was indicated. In the several tests at -100°F and above, OF_2 liquid fill did not occur as expected, since the vapor pressure at such temperatures markedly exceeds tank set pressure.

In summary, although hardware temperature effects the occurrence of hard liquid filling of manifolds and therefore of early all liquid flow through the injector, ignition delays are found nevertheless to be insensitive to hardware temperature. Ignition delay is essentially constant (in the absence of severe oxidizer manifold pressure peaks) and occurs regardless of the occurrence or time of manifold liquid fill.

3. Effect of Propellant Lead/Lag

As expected, the shortest ignition delays (from electrical signal to the leading valve) were obtained with the no-lead condition (Table IV). For an oxidizer lead of 10 msec (electrical signal), the ignition delays with each injector were increased approximately 9 msec over comparable no-lead cases. With a fuel lead, however, the ignition delays were generally longer and quite erratic as a consequence of greater pressure spiking in the oxidizer manifold (Sec. V.A.2.a).

The only chamber pressure spike experienced during the program occurred with an oxidizer lead (Run 37, Fig. 16). As discussed in Sec. V.A.1, the spike is attributed to reaction of the oxidizer, OF_2, with residual combustion deposits from prior runs.

4. Effect of Injector Configuration

The two injectors described in Sec. III.A.2 were tested with the Flox/diborane combination (Table IV). As expected, the single element doublet injector, which has the smaller dribble volume, gave slightly shorter ignition delays than the nine element doublet injector. However, the single element injector was somewhat more prone to pressure peaking in the oxidizer manifold (Sec. V.A.2.a). Neglecting runs affected by the pressure peaks, the ignition delay for the single element injector (no propellant lead) was 20 ± 2 msec versus 22.5 ± 1.5 msec for the nine element injector (Runs 19, 20 and 28 vs. 5, 10, 17 and 18). The difference of 2.5 msec is consistent with the difference between the theoretical fuel manifold liquid fill times for the two injectors. Actual fuel manifold liquid fill times, which are obtained from water hammer pressure peaks that occurred only in runs with hardware conditioned to -100°F and -200°F (Sec. V.B.2), differ between the two injectors by 3 to 3.5 msec (Table IV).

The shorter ignition delays of the single element injector persisted with either an oxidizer or fuel lead although, in the latter case, data scatter was greater.

5. Effect of Design Chamber Pressure

The two thrust chamber configurations tested differed in design chamber pressure: 100 psia and 20 psia. The latter was tested with OF_2 as oxidizer while the former was tested with both oxidizers. Comparable OF_2/B_2H_6 tests with the two chambers and the nine element injector gave ignition delays of 26 ± 1 msec and 29.5 ± 1 msec for the 100 psia and 20 psia chambers, respectively (Runs 31-33 vs. 39, 40 and 43, Table IV).

The fact that the ignition delay time is affected by design chamber pressure indicates that the dominant ignition reactions are gas phase reactions that depend on the concentration of the propellant vapors. In the lower P_{ch} chamber, the preignition pressure rise is slower and leads, therefore, to longer ignition delays.

6. Effect of Propellant Temperature

The propellants were normally conditioned to -320°F for the oxidizers and to -100°F for the fuel. Three runs, Runs 44-46 (Fig. 18), were made with warmer propellants. The nine pair doublet injector and the 100 psia chamber, both conditioned to -100°F, were used for these tests (Table IV). There was no propellant lead. The first run was made with the B_2H_6 at -10°F and cold OF_2. A high pressure peak occurred in the oxidizer manifold causing a long ignition delay of 45 msec. The second run was made with the OF_2 at -150°F and cold B_2H_6. The ignition delay was 26 msec which is similar to the value obtained when both propellants are cold (Runs 31-34). The third run was made with -170°F OF_2 and -10°F B_2H_6 and gave a similar ignition delay time of 25.5 msec.

The lack of any effect of propellant temperature on ignition delay was unexpected provided that the initially flowing propellant was in fact at the desired temperature. Since each propellant valve was conditioned with its respective propellant, proper conditioning was assured. The propellants, however, flowed through the stand-off tubes into an injector which was generally conditioned to a different temperature from the propellants. In flowing through the workhorse injector, the temperature of the propellant tends to approach the injector temperature so that, in the limiting case, the propellant issuing from the injector would be at the final injector temperature. Then, since the initial injector temperature was constant for Runs 44-46, propellant temperature would not be expected to affect ignition delay. In this case, however, injector temperature rather than propellant temperature would be expected to influence ignition delay. Nevertheless, we have seen in Sec. V.B.2 that hardware temperature did not affect ignition delay at least when the oxidizers were at -320°F and the fuel at -100°F. Thus, the results to date indicate that neither hardware temperature nor propellant temperature affect ignition delay time. This unexpected result should be verified such as by varying both hardware and propellant temperatures together.

Despite the lack of an effect on ignition delay, propellant temperature, like hardware temperature, did affect the filling of the manifolds. For example, water hammer pressure peaks in the fuel injector manifold, indicating liquid filling and all liquid flow through the injector orifices, were observed routinely in -100°F hardware tests with -100°F B_2H_6 (e.g. Run 45, Fig. 18) but not with -10°F B_2H_6 (Runs 44 and 46, Fig. 18). Nevertheless, rapid liquid filling of manifolds is apparently not necessary for rapid ignition.

C. START-UP PROCESSES

A descriptive accounting of the physical and chemical processes that are operative during start-up under the test conditions is given below.

Upon application of voltage, a magnetic field begins to form in each propellant valve. After approximately 5 msec, the magnetic field causes the poppet of each valve to cock on its seat. Cocking of the fuel valve is the more severe and it results generally in a low, premature diborane flow which vaporizes in and slightly pressurizes the fuel manifold. A weak fuel vapor environment is created in the thrust chamber and fuel migration into the oxidizer injector manifold prior to oxidizer flow becomes possible.

Approximately 11 msec after voltage application, valve poppet transfer begins. The full open position is reached at approximately 16 msec. With start of poppet transfer, liquid propellant begins to flow into the stand-off tubes leading to the injector manifolds. Since the pressure is low, the propellants undergo vaporization to a degree that depends on the injector temperature and the initial propellant (and prop valve) temperature.

In the case of diborane at an initial temperature of -100°F, the period of vaporization in the fuel manifold is quite short for injector temperatures of -100°F and -200°F. At injector temperatures of 0 and +70°F, vaporization and two-phase injection of the fuel continue through the balance of the recorded time interval (70 msec). In the low injector temperature runs, water hammer pressure peaks in the fuel manifold indicate hard liquid fill at approximately 20 msec and 23 msec in the single element injector and nine element injector, respectively. The manifold fill times are the same whether injector temperatures are -100°F or -200°F. At these temperatures, the diborane vapor pressure is much less than tank set pressure so that no tendency toward boiling exists.

At the warmer injector temperatures (0 and +70°F), the fuel extracts heat from the injector and boils in the manifold until the latter is sufficiently cooled. In the present test system, injector cool-down from either 0 or +70°F as initial injector temperatures was not completed within the recorded run time. Similarly, because of the high vapor pressure of Flox at even -200°F, the lowest initial injector temperature tested, hard liquid filling of the oxidizer manifold was not observed in any Flox run.

The vapor pressure of OF_2 is sufficiently lower than that of Flox that, in the one OF_2 test made with an initial injector temperature of -200°F, manifold liquid filling did occur and at approximately 30 msec after valve signal. However, since ignition in this run occurred at 27 msec, two-phase OF_2 injection occurred until after ignition. In all other OF_2 runs, two-phase injection of the oxidizer occurred also throughout the ignition delay period, and beyond.

In the case of diborane, when manifold liquid filling occurred, it occurred sometimes before and sometimes after ignition. Since ignition delay times were essentially constant in a block of "consistent" tests (such as Runs 5, 18, 10 and 17), ignition is apparently unaffected by the occurrence of hard liquid manifold filling. High speed schlieren movies and flash stills of the flow of very volatile earth-storable propellants into low pressures (Refs. 18-20) indicate qualitatively that, in the region of the impingement point, there is little difference between a stream that is flowing all liquid through the injector orifice and a stream that is flowing as a dense two-phase mixture through the orifice. Both streams undergo fine atomization due to internal boiling in the liquid and become greatly enlarged, bushy streams of vapor and small droplets.

As mentioned above, diborane vapor from the premature low fuel flow apparently migrates into the oxidizer manifold prior to oxidizer flow. In the case of a programmed fuel lead, fuel migration into the oxidizer manifold is aggravated. When the oxidizer flows, reaction occurs within the manifold generating pressure peaks which are worse with the fuel lead condition.

Another source of contaminants in the oxidizer manifold is condensed phase material which forms during the combustion process and pulse tail-off and which disperses throughout the thrust chamber as finely divided colloidal particles. The material by analysis is primarily amorphous boron which is a natural product of fuel rich combustion, a condition which always occurs during pulse tail-off in the present system. Since pressure peaking in the oxidizer manifold is somewhat worse with a previously run injector than with a clean injector, the condensed phase combustion residues in the manifold must contribute. Reactivity of OF_2 with the combustion residues was established by a singly flowed OF_2 test in which obvious reaction occurred.

The occurrence of severe pressure peaks in the oxidizer manifold causes a momentary interruption in oxidizer flow which results in delayed ignition in the thrust chamber. The manifold pressure peaks give rise to potential damage to propellant valves and injector face. Pressure peaking was slightly worse with Flox than with OF_2.

As is the case with N_2O_4/N_2H_4-type propellants (Refs. 18-20), ignition of OF_2/B_2H_6 is affected by design chamber pressure (i.e. throat area at constant L*) indicating that the dominant ignition reactions are gas phase reactions. Therefore ignition depends upon pre-ignition pressurization of the chamber due to propellant vaporization and possible pre-ignition reactions.

One strong ignition pressure spike occurred during the program. The OF_2 run had a programmed oxidizer lead and, in view of the demonstrated reactivity of the oxidizer with the condensed phase combustion residues, it is believed that the ignition spike is a reoccurrence of the latter. Verification is required, however.

D. DESIGN CONCEPTS AND OPERATIONAL PROCEDURES

Due to the exploratory nature of the program, tests were conducted under a wide range of conditions. Thus, the number of samples for a given set of conditions is necessarily small. Significant trands were observed, nevertheless, which bear directly on engine design from the standpoints of ignition and stability. Operational procedures were also shown to have a direct effect on performance.

Short ignition delays are favored by small injector dribble volumes and high design chamber pressure. Since ignition depends upon rapid pre-ignition chamber pressurization, other factors such as fast-acting valves and high initial propellant flows (i. e. flow control by system ΔP as opposed to cavitating venturis) also promote short ignition delays.

To eliminate or minimize pressure peaking in the oxidizer manifold, migration of fuel and condensed phase combustion residues into the oxidizer manifold must be avoided. For a given injector through-put area, flow impedance is greater with many small diameter holes of long length-to-diameter ratios than with a single larger diameter hole with a shorter l/D. In addition, fuel migration can be minimized by a low fuel temperature which presumably is effective by lowering the fuel vapor pressure. Also, fuel migration can be avoided by providing for simultaneous propellant entry or, better, a slight oxidizer lead.

Condensed phase combustion residues (primarily amorphous boron) aggravate oxidizer manifold pressure peaking and apparently can lead to ignition pressure spikes in the thrust chamber. To minimize the formation of this material, fuel-rich tail-offs should be avoided as far as possible.

Low hardware temperatures (-100°F and below) avoid high frequency pressure oscillations in the oxidizer manifold. The oscillations occurred only with OF_2 at hardware temperatures of 0 and +70°F and may be associated with injector cool-down phenomena which are avoided by initially cold hardware.

In summary, from the standpoints of ignition behavior and system stability during start-up, an engine for OF_2/B_2H_6 multiple-pulse operation in space should be designed with a high chamber pressure and a minimum dribble volume, multiple element injector having small diameter, long l/D orifices. The system should provide for simultaneous propellant injection or a slight oxidizer lead, cold diborane, cold hardware and an oxidizer-rich tail-off. Other usual features of high response engines such as fast-acting valves and flow control by system ΔP are of course necessary.

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VI. CONCLUSIONS

The following conclusions are drawn based on the results of the predominantly experimental investigation.

The ignition delays of Flox/B_2H_6 in 100-lb thrust engines fired at simulated altitudes in excess of 250,000 ft are slightly shorter than those of OF_2/B_2H_6 under comparable conditions. The dominant ignition reactions appear to be gas phase reactions so that the shorter Flox/B_2H_6 delays may be attributed to the higher vapor pressure of Flox and the fluorine-enriched vapor which results from preferential vaporization of the mixed oxidizer.

Oxygen difluoride reacts spontaneously with the condensed phase combustion residue formed during prior pulses. The residue found in the test system was primarily amorphous boron which probably formed mainly during the fuel-rich tail-offs.

One ignition spike was observed but as it occurred in a run with a programmed oxidizer lead it is suspected that the pressure spike was due to reaction of OF_2 with combustion residue.

Random high pressure peaks occurred in the oxidizer manifold and occasionally caused delayed ignition due to momentary interruption of the oxidizer flow. No damage to the propellant valve or workhorse injector was experienced but this remains a distinct possibility especially with flight-weight hardware. The oxidizer manifold pressure peaks are attributed to both fuel entering the oxidizer manifold prior to oxidizer flow and to combustion residues entering during tail-off of the previous pulse.

High and low frequency oscillations in the oxidizer manifold were observed with OF_2 under certain operating conditions. The oscillations appeared also in the thrust chamber but with reduced amplitudes.

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VII. RECOMMENDATIONS

Several factors pertinent to vacuum ignition of OF_2/B_2H_6 in space-ambient engines that were either outside the scope of the present program or require further study beyond that permitted during this eight-month effort are enumerated below:

1. Because of its apparent role in both thrust chamber and oxidizer manifold pressure spikes, the condensed phase combustion residue requires further study to determine its composition, where and when it forms during a pulse, and its accumulation rate in the oxidizer manifold and chamber walls.

2. The apparent and unexpected independence of engine ignition delays on both hardware and propellant temperatures should be verified by further testing at temperature extremes.

3. The effects of system configuration changes and propellant valve types, such as high response, torque motor driven valves and positive seal, explosively actuated valves, upon ignition delay time and oxidizer manifold phenomena need to be determined.

4. Further experimental and analytical work is required to better define starting mechanisms. The experimental work should include additional instrumentation such an optical ignition detector, optical detector for entry of liquid propellants, and some high speed movies of the ignition processes within the thrust chambers. The analytical work should include a mathematical description of the starting processes to permit economic evaluation of design parameters of future spacecraft engines.

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APPENDIX A

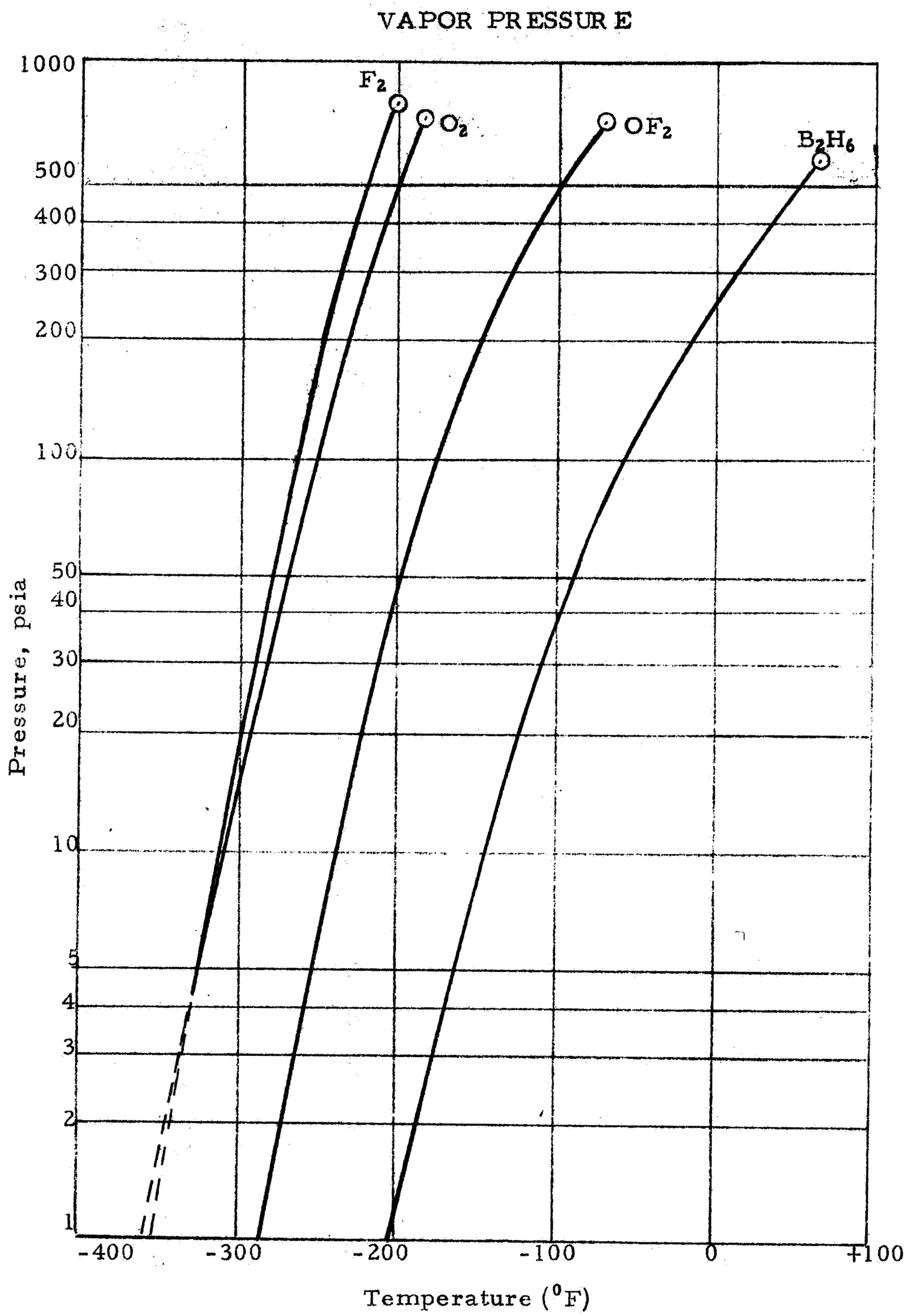
PROPELLANT PROPERTIES

TABLE AI. SELECTED PROPELLANT PROPERTIES

Propellant	Oxygen	Fluorine	Oxygen Difluoride	Diborane
Formula	O_2	F_2	OF_2	B_2H_6
Molecular Weight	32	38	54	27.7
Freezing Point (^{0}F)	-361.8	-364	-370.8	-264.8
Boiling Point (^{0}F)	-297.4	-306.6	-228.6	-134.5
Critical Temperature (^{0}F)	-181.2	-200.6	-72.4	+62.1
Critical Pressure (psia)	730.6	808	718.6	581

O_2, F_2 and OF_2 data from Battelle Memorial Institute Liquid Propellants Handbook.

B_2H_6 data from Callory Chem. Corp. Technical Bulletin C-020.



⊙ Critical Point

Figure A-1. Propellant Vapor Pressures as a Function of Temperature

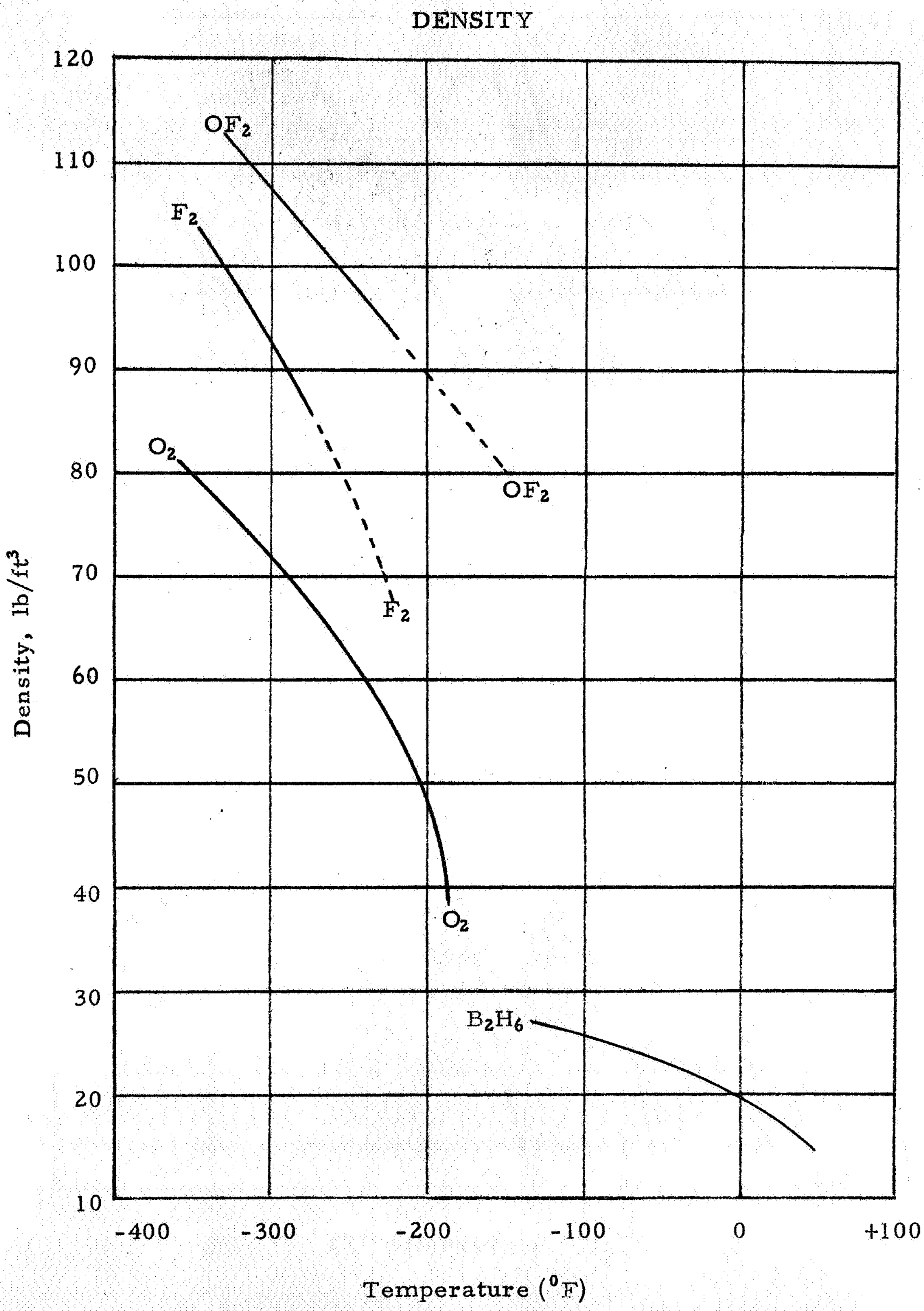
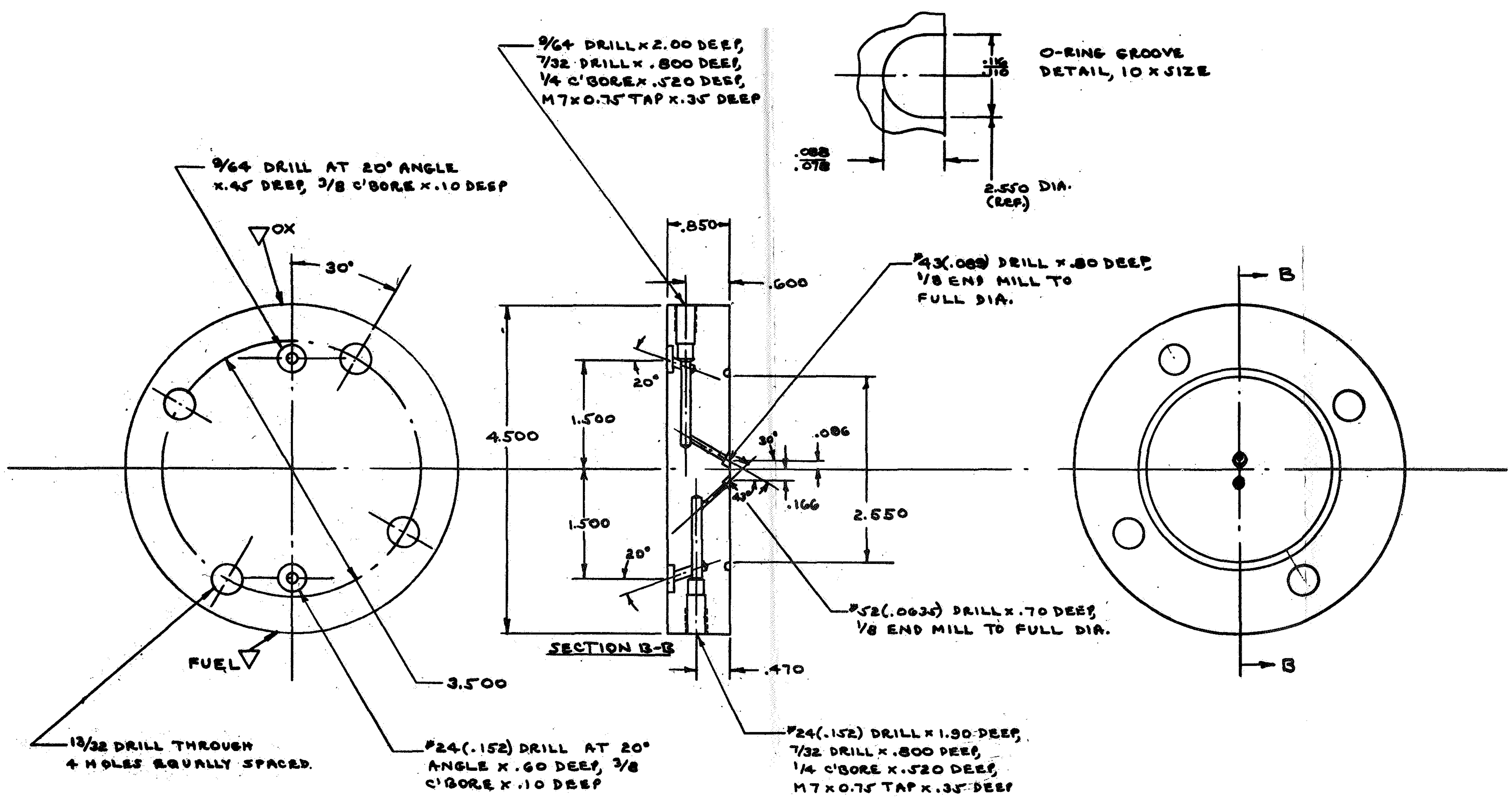


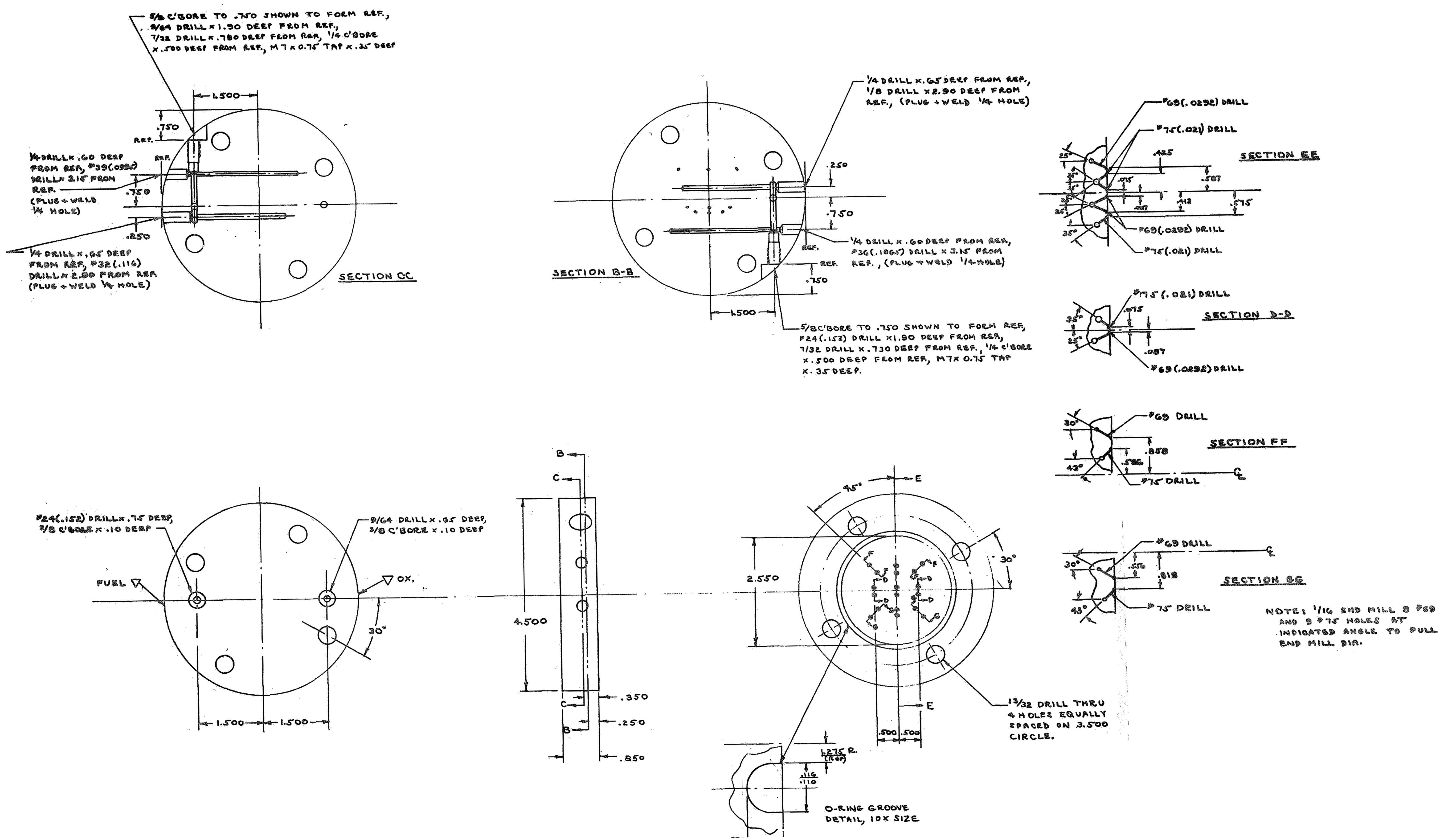
Figure A-2. Propellant Densities as a Function of Temperature

APPENDIX B

INJECTOR DRAWINGS



9/64 DRILL x 2.00 DEEP, 7/32 DRILL x .800 DEEP, 1/4 C'BORE x .520 DEEP, M7x0.75 TAP x .35 DEEP
O-RING GROOVE DETAIL, 10 x SIZE
.088
.078
2.550 DIA. (REF.)
9/64 DRILL AT 20° ANGLE x.45 DEEP, 3/8 C'BORE x .10 DEEP
OX
30°
.850
.600
#43(.089) DRILL x .80 DEEP, 1/8 END MILL TO FULL DIA.
B
20°
4.500
1.500
1.500
30°
.086
45°
.166
2.550
20°
#52(.0635) DRILL x .70 DEEP, 1/8 END MILL TO FULL DIA.
SECTION B-B
.470
FUEL
3.500
13/32 DRILL THROUGH 4 HOLES EQUALLY SPACED.
#24(.152) DRILL AT 20° ANGLE x .60 DEEP, 3/8 C'BORE x .10 DEEP
#24(.152) DRILL x 1.90 DEEP, 7/32 DRILL x .800 DEEP, 1/4 C'BORE x .520 DEEP, M7 x 0.75 TAP x .35 DEEP



5/8 C'BORE TO .750 SHOWN TO FORM REF., 9/64 DRILL x 1.90 DEEP FROM REF., 7/32 DRILL x .780 DEEP FROM REF., 1/4 C'BORE x .500 DEEP FROM REF., M7 x 0.75 TAP x .35 DEEP
1/4 DRILL x .60 DEEP FROM REF., #39(.0995) DRILL x 3.15 FROM REF. (PLUG + WELD 1/4 HOLE)
1/4 DRILL x .65 DEEP FROM REF., #32(.116) DRILL x 2.90 FROM REF. (PLUG + WELD 1/4 HOLE)
SECTION CC
1/4 DRILL x .65 DEEP FROM REF., 1/8 DRILL x 2.90 DEEP FROM REF., (PLUG + WELD 1/4 HOLE)
1/4 DRILL x .60 DEEP FROM REF., #36(.1065) DRILL x 3.15 FROM REF., (PLUG + WELD 1/4 HOLE)
SECTION B-B
5/8 C'BORE TO .750 SHOWN TO FORM REF., #24(.152) DRILL x 1.90 DEEP FROM REF., 7/32 DRILL x .730 DEEP FROM REF., 1/4 C'BORE x .500 DEEP FROM REF., M7 x 0.75 TAP x .35 DEEP.
#69(.0292) DRILL
#75(.021) DRILL
#69(.0292) DRILL
#75(.021) DRILL
SECTION EE
#75(.021) DRILL
#69(.0292) DRILL
SECTION D-D
#69 DRILL
#75 DRILL
SECTION FF
#69 DRILL
#75 DRILL
SECTION GG
NOTE: 1/16 END MILL 8 #69 AND 8 #75 HOLES AT INDICATED ANGLE TO FULL END MILL DIA.
#24(.152) DRILL x .75 DEEP, 3/8 C'BORE x .10 DEEP
9/64 DRILL x .65 DEEP, 3/8 C'BORE x .10 DEEP
FUEL
OX.
13/32 DRILL THRU 4 HOLES EQUALLY SPACED ON 3.500 CIRCLE.
O-RING GROOVE DETAIL, 10X SIZE

APPENDIX C

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